Network-RTK Positioning for Automated Driving (NPAD)

Public report

Project within Electronics, Software and Communication

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Content

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1 Summary

Future automated vehicles and advanced driver assistance systems are highly dependent on sensors to detect their environment as well as robust, accurate, and cost-effective sensor systems for positioning. No single sensor solution is enough to robustly and accurately determine the vehicle's position relative to its surroundings and objects on the road in all environments and situations. It is particularly important to be able to position the vehicle relative to maps and road layout in order to be sure that the vehicle is in the correct desired position on the road. For the sole purpose of automated driving and collision avoidance, onboard sensors providing the relative position of the vehicle in relation to the map and objects are typically providing an adequate solution. However, in other use cases, an absolute position is vital. Examples include coordinated mobility with numerous vehicles, sharing of sensor data, evaluation of autonomy algorithms, etc.

Global Navigation Satellite systems (GNSS) provide a key technology that enables an absolute position estimate and Network-RTK (Real Time Kinematic) has the potential to meet the requirements of cost, accuracy, and availability. This technology is based on correction data being received from a fixed reference station via e.g. mobile communication. Current implementations have been driven by requirements from applications which operate within a limited region for lengthy periods of time, such as surveying and precision agriculture. These applications can tolerate relatively long initialization times and can afford expensive equipment.

The mass market wants to benefit from infrastructure in place for these applications, but the requirements are somewhat different. Problems occur when the device moves from the coverage area of one reference station to another and reinitialization must be made. Consumer devices must also deliver similar performance with inexpensive components. In addition to this, the existing public-sector system for distribution of correction data, in Sweden governed by Lantmäteriet/SWEPOS, is not designed for handling a large number of clients and efficiently distributing correction data to these clients based on their location.

The telecom industry in 3GPP (Third generation partnership project) is currently addressing the need for a scalable provisioning of network RTK corrections. Based on the 3GPP specification, the project aimed to develop, implement, test and demonstrate an efficient distribution system for Network-RTK correction data in order to enable cm-level accuracy GNSS positioning for a large number of mobile platforms e.g. automated vehicles.

The NPAD project has:

- Leveraged the existing Lantmäteriet/SWEPOS GNSS reference infrastructure to implement a virtual network of reference stations that provided coverage over selected test areas suitable for supporting a large number of simultaneous users.
- Implemented a scalable GNSS correction data provisioning based on the ongoing work in 3GPP that provides correction data from the reference network to mobile devices;
- Developed test cases for automated vehicle platforms related to positioning and implemented demonstrators;
- Investigated tools and methods for validating the accuracy of integrated GNSS positioning and navigation systems.

The project was coordinated by RISE Research Institutes of Sweden and involved besides Lantmäteriet and AstaZero the following industrial partners: AB Volvo, Caliterra, Einride, Ericsson, Scania, and Waysure.

2 Sammanfattning på svenska

Framtidens automatiserade fordon är starkt beroende av dels sensorer för att detektera sin omgivning och dels robusta, noggranna och kostnadseffektiva sensorsystem för positionering. Särskilt viktigt är det att kunna positionera fordonet relativt kartor och vägens utformning för att t.ex. vara säker på att fordonet befinner sig i rätt önskad position på vägen.

Satellitbaserade positioneringssystem (GNSS) är en viktig nyckelteknologi för att möjliggöra automatiserade fordon. Nätverks-RTK (Real Time Kinematic) är en GNSS-teknologi som har potential att kunna svara mot krav på kostnad, noggrannhet och tillgänglighet. Denna teknologi bygger på att korrektionsdata från en fast referensstation kan tas emot via t.ex. mobil kommunikation. Dock uppstår problem när fordonet rör sig från en referensstations täckningsområde till ett annat och om-initialisering måste ske mellan fordonet, referensstationen och satelliterna. Dessutom är dagens system för distribution av korrektionsdata ej byggt för en massmarknad av fordon och andra mobila enheter. Inom 3GPP arbetas det nu med standardisering kring hur korrektionsdata skulle kunna distribueras via mobilnätet vilket skulle kunna möjliggöra positionering på cm-nivå för en massmarknad.

Projektet har sammanställt kravbilden utifrån automatiserade fordon, undersökt hur befintliga system för distribution av korrektionsdata skall anpassas och hur en komplett arkitektur skall se ut för distribution via mobilnätet. Demonstratorer har därefter implementerats och tester för att demonstrera tekniken dels på AstaZero och dels längs utvalda vägsträckor har utförts. Testerna har validerat den tekniska lösningen och testat både basstationsbyte och skifte mellan referensstationer. Resultat från projektet har kunnat användas i nya projekt inom andra domäner som t.ex. sjöfart och drönare.

3 Background

There are three challenges that future transport systems must overcome; environmental impact, safety, and congestion. An important part of addressing these challenges is the development of active safety and automated driving (AD) systems which assist and replace the driver in both normal and critical situations. According to the Swedish Government in 1997 this same development is required to meet Vision Zero. Such active safety and automated driving systems have already shown a reduction in both the number and extent of injuries and insurance costs [1]-[2]. The suite of sensors which Advanced Driver Assistance Systems (ADAS) are furnished with include cameras, Radar, Lidar, ultrasonic, and of particular interest in this project, GNSS. As the requirements for AD systems become more stringent, the subsequent requirements on each of the sensor systems increase accordingly. Requirements for robustness, integrity, latency, accuracy and how information should be interpreted become more demanding.

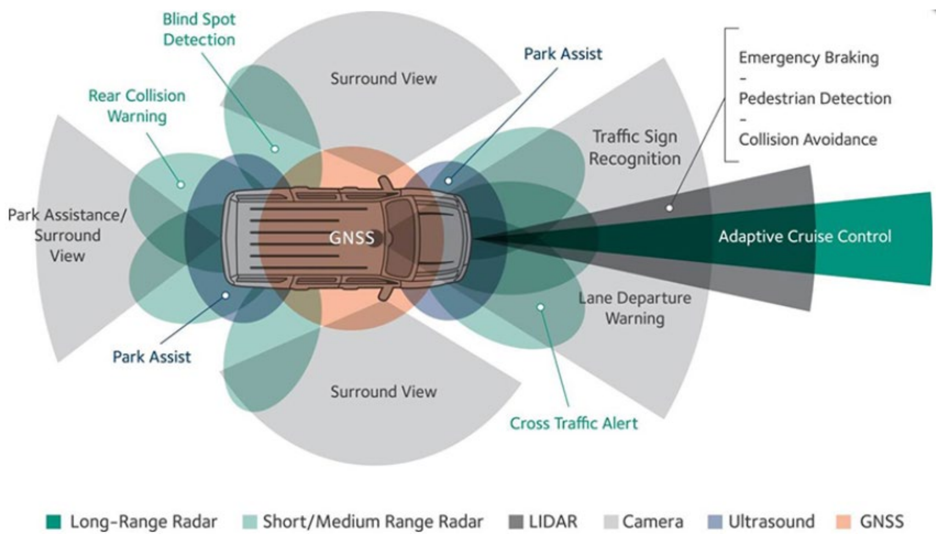

Figure 1 Sensors for automated vehicles[1]

Future automated vehicles and advanced driver support systems build on integration of complementary technologies to position the vehicle absolutely (globally referenced) and relative to eventual obstacles and obstructions. No technology on its own can meet the requirements for all driving environments and situations on its own. Integration of technologies provides redundancy in the system, where should a single technology struggle, the combination of technologies can still meet requirements. Furthermore, the combination of technology also increases robustness in the system. In modern implementations the previously mentioned sensors are used for relative positioning of the vehicle to obstructions. The same sensors can also be used to position the vehicle relative to map information, so called Vision Aided Navigation. This navigation method has drawbacks, such as outdated map information, sensor obstruction due to vehicles or weather conditions, and sabotage. From a robustness perspective, it is extremely important to combine information sources to maximize the operational capability in all situations, environments, and use cases. Combining information which originates from uncorrelated sources is also in itself an added layer of protection against sabotage.

Global Navigation Satellite Systems (GNSS), Satellite based Augmentation Systems (SBAS) and Ground based Augmentation systems (GBAS) have massive potential and are key and enabling technologies for Automated Driving. High accuracy (cm error) GNSS receivers are expected to impact the automated driving industry considering the increase in availability and reduction in price these systems have experienced in recent years.

Real Time Kinematic (RTK) [3] is a well-established technique in the building and surveying industry and is included in standard equipment today. The technique was named RTK to differentiate it from the post-processing techniques used on data collected from static antennas and was revolutionary when it came to market in the early 1990's. However, the current use of the technique has a limited operational area and does not require continuous and robust positioning. The technique is based on two aspects, the differencing of measurements between satellites and receivers to remove systematic errors, and the estimation of the carrier wave integer ambiguity.

[1] http://www.novatel.com/industries/autonomous-vehicles/#technology

This first aspect requires communication of measurements between the mobile device and a reference station.

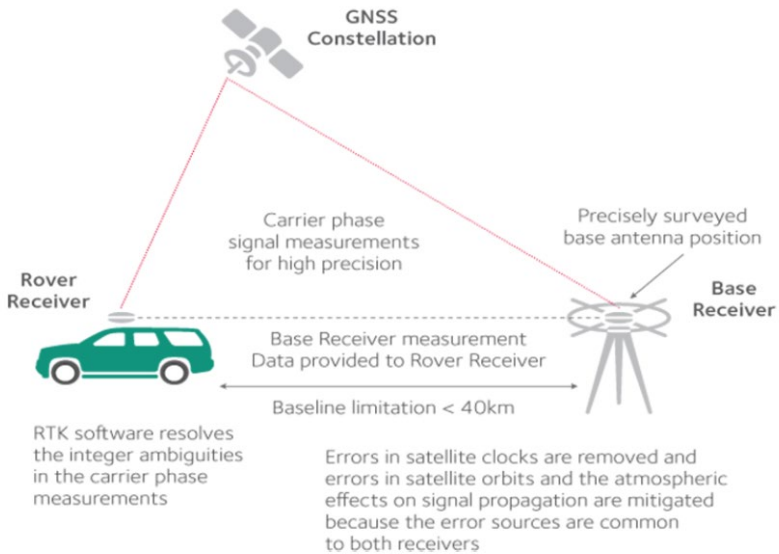

Figure 2 Principles for RTK[2]

A mobile device may change which reference station it receives correction data from because, for example, the distance between it and the reference station is too long to allow adequate cancellation of errors, it wishes to change the reference network operator, or it detects errors in the current corrections. When a change occurs, the position and ambiguity solution must be re-initialized. For multi-frequency systems this can take 10 seconds, but for single frequency systems this can be 5 minutes or more. Multiple frequency systems are often much more expensive. Any re-initialization period means a probable degradation in the positioning accuracy from a few centimeters to many decimeters. Anything that can be done in the implementation of the server or the receiver to facilitate a seamless handover is highly beneficial for mobile devices. This project will implement this feature. Network RTK is a development of ordinary RTK with a single reference station featuring a network of reference stations. There are several concepts for taking advantage of the stations in a network approach, where the most commonly used one is called Virtual Reference Station (VRS), see Figure 3.

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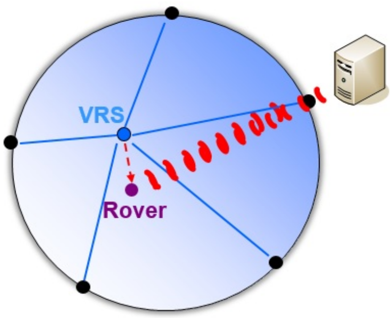
[2] http://www.novatel.com/industries/autonomous-vehicles/#technology



Raw GNSS data is gathered continuously by a network of reference stations and transferred to a central RTK software. After the rover has been turned on it transmits a navigated position to the control centre. Dependent on the navigated positions geographical location, the control centre chooses the relevant reference stations for the location and data is processed and phase ambiguities between reference stations are fixed. Interpolation methods are used to predict the atmospheric delays in the area. A Virtual Reference Station (non-physical) is created for the navigated position of the rover. The rover interprets the VRS data as a single reference station.

Figure 3 Positioning concept – Virtual Reference Station (VRS)

The ability for devices to be able to determine their position is becoming ubiquitous. Of the possible technologies that can estimate position, GNSS, is the obvious choice for outdoor applications due to its commoditization, accuracy and global availability. The development of GNSS is rapid with the intention to provide better accuracy, robustness and integrity. There are more satellites being launched into orbit, with more frequencies and capabilities and ground systems are also being modernized to provide more accurate orbital and clock information, as well as more accurate modelling of atmospheric parameters which will also improve performance.

If the existing procedures for NRTK are adopted in mass market scenarios, there will be an extensive exchange of messages between the devices and the NRTK server, which both can result in a significant load of the communication links causing delays in the provisioning of the corrections. Furthermore, the NRTK server will face challenges processing all the requests and calculating the appropriate correction data adopted for each device. Figure 4 illustrates the scalability issues with the existing procedures.

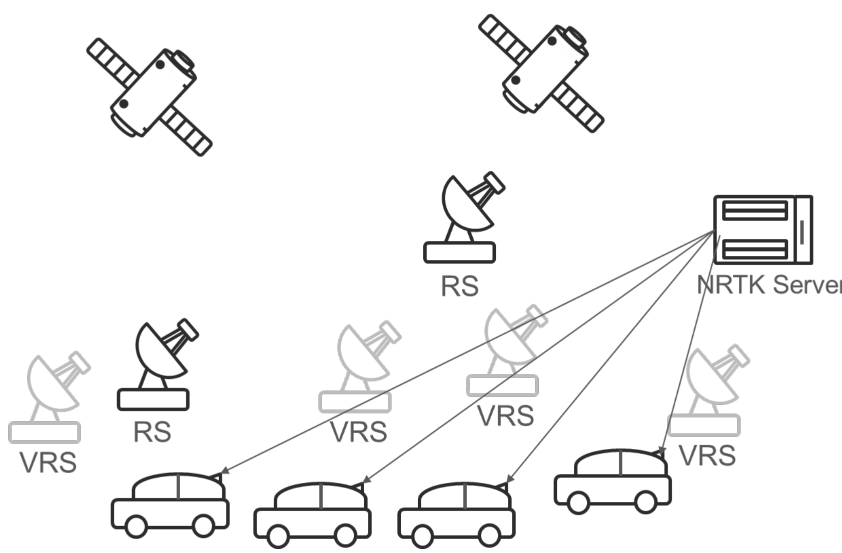


Figure 4 The current NRTK procedures scales badly.

Currently, 3GPP [4][5] are working on procedures to enable the location server in the cellular network architecture to provision NRTK corrections via the cellular network. The work is part of 3GPP Rel. 15 and concerns both LTE/4G as well as 5G. The work will be completed during 2018 for LTE. Two modes of provisioning are being specified – unicast and broadcast. For unicast, the location server acts as a proxy and maintains updated correction data to be provisioning on a per device basis using the efficient information encoding and signaling of cellular networks. In order to support full scalability, the information, which is highly regional, can also be broadcasted as part of the system information from the cellular network to allow all devices to take advantage of the same transmission of the information.

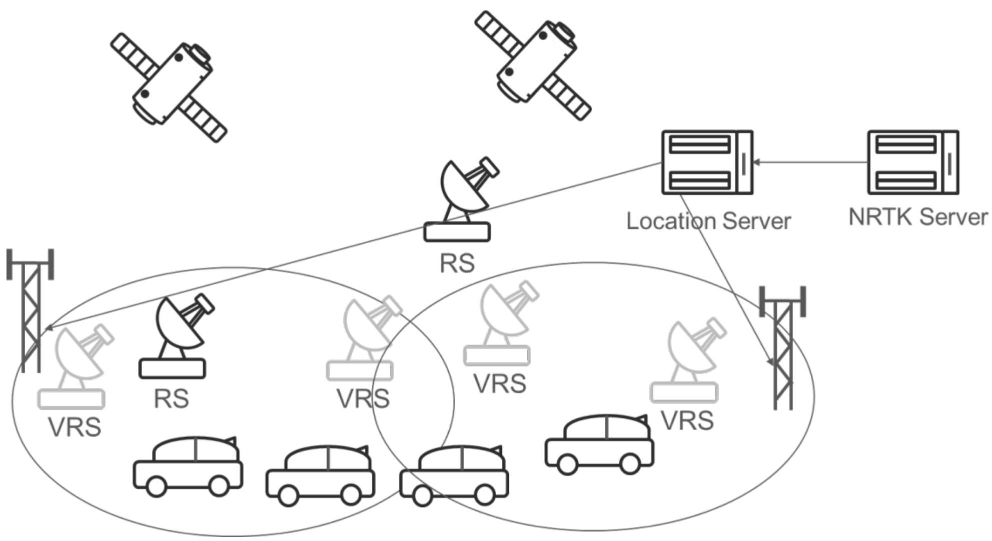


Figure 5 Scalable solution with intermediate processing in a location server and provisioning based on the cellular network.

4 Project Realization

This section describes the organization and execution of the NPAD project.

4.1 Organization and management

The NPAD project organization was kept as efficient as possible, but still followed the current best practice for this type of research. Project management structure was composed of:

- Steering Committee
- Project Manager
- Work package leaders

The steering committee consisted of one representative from each project partner. This representative had full power to decide on behalf of their respective organizations in matters of project management. The responsibility of the steering committee was to comprehensively ensure that the project reached its goals on time and with the right quality. The steering committee had representatives from all partners.

The project manager had the daily responsibility to ensure that the project reached all parts of the progress the planning prescribed and handled all reporting and contact with VINNOVA and reported to the steering committee, if needed.

Each work package leader was responsible for planning and implementation of the respective work packages and ensured that the associated deliverables were undergoing internal review. Work package leaders were responsible for ensuring that work packages followed schedules and quality goals and reported any deviation during the project to the project manager.

4.2 Communication

Weekly Skype meetings were held throughout the project on every Wednesday 15:00-15:45 from May 2018 to June 2020. For the last period between July 2020 to December 2020, bi-weekly meetings were held. During these meetings a Trello board was used to follow up activities within the project. In addition to this, several physical meetings have also been held:

Date	Location	Description
2018-05-03	RISE Borås	Project Kick-Off Meeting
2018-09-07	Lantmäteriet Gävle	Project Meeting
2018-11-13	Skype	VRS Workshop
2018-12-17	Ericsson Linköping	Project Meeting
2019-05-07	RISE Göteborg	Project Meeting
2019-09-12	RISE/AstaZero Borås	Project Meeting
2020-01-21	Skype	Meeting with Trimble
2020-03-05	AstaZero	Project Meeting

Since March 2020, no physical meeting could be held due to restrictions caused by the Covid-19 pandemic. A DropBox area was set up for storage of project artefacts and for sharing of data.

4.3 Work Packages and Execution

The six work packages carried out in the project are outlined in Table 1 below.

Work Package	**Duration (months)**	**Activities**	**Results/deliverables**
WP1 Project management and Dissemination	Entire project	Management of the work performed in the project.	Status reports, presentations
WP2 Elicitation of Positioning Requirements	6	Definition of requirements for positioning of Automated Driving applications in terms of accuracy, precision, availability etc.	Positioning requirements and requirements of the correction data distribution system.
WP3a Correction Data Distribution System Implementation	8	Design and implementation of the GNSS Network RTK Correction Data Distribution System by leveraging: - the existing Lantmäteriet GNSS reference infrastructure by implementing a virtual network of reference stations, providing coverage over the test area - the existing location server by implementing a prototype for scalable Network RTK correction data distribution to support a large number of simultaneous and mobile users. - the existing integrated GNSS positioning and navigation systems platforms by implementing and utilizing the scalable GNSS Network-RTK correction data.	System Design Reports
WP3b RTK GNSS Positioning Platforms Implementation	8	Integration Navigation solutions into selected GNSS Positioning Platforms	System Implementation Reports
WP4 Integration and Test	9	Development of test cases for automated vehicle platforms related to positioning Develop methods for validating the accuracy of integrated GNSS positioning and navigation systems	Integration Plans and Test Procedure Documents
WP5 Validation and Demonstration	8	Test and validation of the Correction Data Distribution System with integrated GNSS positioning and navigation systems in mobile platforms e.g. automated vehicles. Final Demonstration	Final seminar and Final Report.

Table 1 NPAD Work Packages

The work package structure and their internal dependencies are outlined in Figure 4 below:

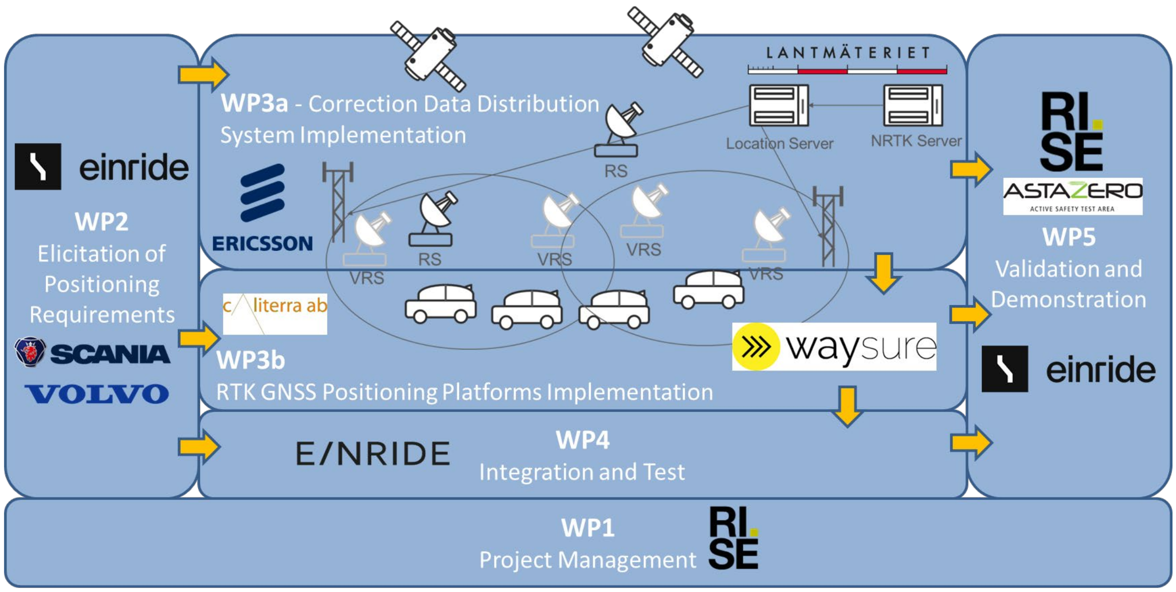


Figure 4 NPAD Work package structure

4.4 Challenges and Experiences

The main challenges within the project has been to have enough time and resource to analyze all the data from all measurements carried out within the project and to cope with the impact of the Covid-19 pandemic, which affected the planning and execution of tests during 2020. The focus has been to secure data by planning and coordinating all the measurement activities during test activities at AstaZero as well along highway no 40 between Gothenburg and Borås.

5 Objective

The development of Network-RTK GNSS based positioning technologies, an absolutely necessary sensing technology for AD vehicles, relies on a system for distribution of correction data that can handle the increasing requirements of a large number of automated vehicles or other mobile platforms as well as reliable and efficient testing to validate the system performance.

The objective of the project as it was outlined in the application was to enable cm-level Network-RTK positioning for a large number of automated vehicles or other mobile platforms by applying the standard developed by 3GPP and adapting the existing infrastructure provided by Lantmäteriet/SWEPOS.

NPAD main objectives are outlined below:

- Development of a system and infrastructure that provides cm-level positioning for a large number of mobile platforms which is not only suitable for automated vehicles using GNSS as a sensor, but also provides a reference for testing automated vehicles which do not rely on high accuracy GNSS as a sensor.
- Development and testing of the system for the upscaling of large volumes of automated vehicles and their needs of cm-level positioning.
- Promotion of a cross-industrial cooperation between the project partners which includes research institutes, automotive industry, telecom industry as well as SME's.

These objectives have not changed during the project and have been met.

6 Results and deliverables

6.1 Positioning Requirements for Automated Driving

6.1.1 Background

For an autonomous vehicle to navigate safely there is a need for highly accurate positioning. With GNSS based positioning, enough good satellites need to be in view of the receiver and corrections needs to be available and reliable. This will vary between different environments and scenarios.

This section describes the requirements of a proposed GNSS positioning solution using cellular based broadcasted corrections from virtual reference stations. These requirements are derived from specific use cases associated with the vehicle OEMs that form part of the consortium, namely Scania, AB Volvo and Einride.

6.1.2 Definitions

6.1.2.1 Position

Where the platform is, with respect to a reference frame, often represented in Cartesian or Polar coordinate format. For example, latitude, longitude, altitude.

6.1.2.2 Location

Where the platform is, with respect to its surroundings. For example, in the center lane.

6.1.2.3 Situation

The location of the vehicle with respect to its surroundings, and information about how the location will change in the future. For example, indication of potential collisions, or inability to localize the ego vehicle.

6.1.3 Overview

6.1.3.1 System Overview

The complete system consists of a network component for generation and distribution of the correction data, and clients to receive and use the correction data along with GNSS data transmitted from the satellites installed in autonomous vehicles. Where appropriate this separation shall be used to define the requirements.

6.1.3.2 Key uses of GNSS Positioning in Autonomous Driving

GNSS can be used in several ways for autonomous applications.

1. To provide a position relative to map data to localize the ego vehicle for autonomy.
2. To provide a common reference frame to share information.
3. As part of a reference data collection set to harvest information.
4. For calibrating systematic errors in other motion and timing technologies.
5. As a reference system for testing other positioning and location technologies.

The most stringent of these applications for requirements is no 1. The exception being accuracy for application no 5. Application no 1 will be used to set the requirements for the project.

Position

Differing techniques within GNSS positioning can provide accuracies varying from 5 to 10 meters down to 2 cm and below. The varying techniques can also provide absolute position, with respect to a global reference system such as WGS84, or relative position with respect to a reference GNSS receiver. In case of relative position, should the position of the reference receiver be accurately known with respect to a wider reference frame (WGS84, SWEREF99, EUREF, etc.) then the position with respect to that reference frame is also known. Whichever technique is decided upon, for autonomous driving, the position must be relatable to the map data.

GNSS signals are not ubiquitously available, and therefore it cannot be guaranteed that GNSS will always be able to provide a position. Due to the environmental affects causing signal availability, availability should not be specified without a description of the environment. Even when signals are available, they may not have the properties that allow for high accuracy positioning. Therefore, accuracy should also not be specified without a clear description of the environment. Considering varying availability and accuracy, integrity is a more important requirement, where the GNSS positioning system can communicate the quality of its position estimate accurately.

GNSS positioning provides a single position estimate related to the phase center of the receiving antenna, or should the application call for multiple antennas. This/these positions must be related other sensors in the platform and the platform extremities. In the case of platforms which do not have a rigid body, effects of the flexion and extension of the body may need to be considered in the positioning algorithm, so-called variable lever arm.

Time

GNSS is also an accurate source of time. This is useful for synchronization of data within an autonomous vehicle and between autonomous vehicles.

6.1.4 OEM Use Cases

This section outlines the platforms that the vehicle OEMs manufacture, and a brief outline of the how and where they are used.

6.1.4.1 Einride

Einride provides transport as a service where their customers pay for goods to be transported between two pre-determined locations, often via a known route. This could be within the boundaries of a large site, such as a manufacturing plant or large warehouse store, or between sites such as a port to a depot or delivery hub.

The Einride Pod, which is the vehicle associated with this service, is 2.5 meters wide, 3.8 meters high and 7.3 meters long. It has a rigid body connecting the body of the vehicle to the chassis. The Einride Pod is designed to cover situations with low-speed fenced-off operations as well as motorway speeds of 80 km/h autonomously. During the development phase, autonomous driving will be monitored remotely by an operator. This operator can also assist the vehicle when complex traffic situations are encountered.

6.1.4.2 Volvo

The Volvo Group is one of the world’s leading manufacturers of trucks, buses, construction equipment and marine and industrial engines. Volvo equipment is operational globally in logistics services, construction, mining, public transport etc. Volvos autonomous truck will operate worldwide in a wide variety of scenarios. As safety is a primary concern autonomous trucks will most likely initially be introduced to the markets in confined and controlled areas like ports, distribution centers and mines. This means that the trucks will have to transit between indoor and outdoor environment regularly and partially blocked sky and multipath will be present. From there, automation will move out into controlled set routes with low density traffic on public roads, like bus routes or well-defined transport routes. As automation levels increase and we move to driverless vehicles, higher demands on positioning will be necessary.

Trucks (Tractor/Trailer)

The main use case for transport vehicles is goods transport between transport hubs such as ports, airports, and depots.

The tractor component is often around 2.55m wide (including wing mirrors) and 3 meters high but can vary from model to model. The length of the combined vehicle is determined by the trailer. The tractor has suspension isolating the drivers cab and body of the vehicle from the chassis. The trailer can be single part or multi part and on European roads can take the lengths described in Figure 5.

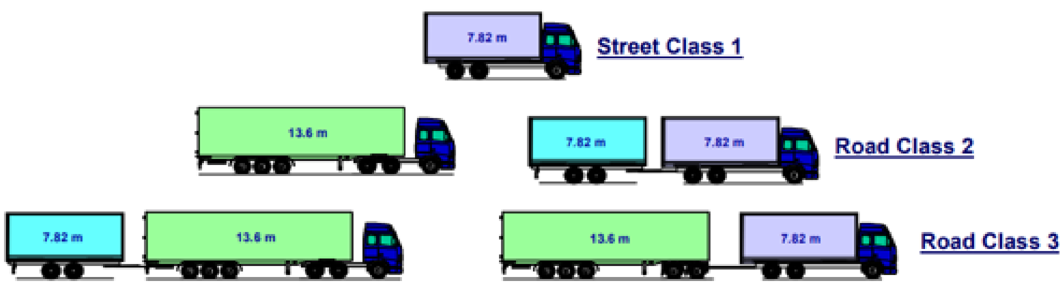


Figure 5 European maximum truck lengths [6]

Buses

Often metropolitan/inner-city and suburban transport. Can be two-part body on a hinged chassis (bendy bus) with soft suspension between the bodies and chasses.

Coaches

Long distance, motorway driving applications. Soft suspension between the complete single piece body and the chassis.

Construction Equipment

Volvo also produces a wide variety of construction equipment, varying from dumpers, tipper and diggers amongst others. The diversity of these platforms means that their size and shape shall not be considered here. However, these are expected to operate in construction and mining operations. Construction could take place in any environment from highly urbanized (Inner city) to rural/coastal. Mining is often rural, where the environment is defined by the mine itself which may consist of tunnels and /or large open pits in the case of open cast mining.

6.1.4.3 Scania

With the aim to lead the shift towards a sustainable transport system, Scania builds its business while creating value for customers, employees and society. Delivering customized heavy trucks, buses, engines and services, focus is always on efficient, low-carbon solutions that enhance customer profitability. R&D operations are mainly located in Södertälje, Sweden, with some 3,700 employees. The aim is to develop high-quality products and solutions for specific customer demand with short lead times from idea to launch.

Trucks (Tractor/Trailer)

Most of the vehicles manufactured and sold by Scania are trucks. Scania does not offer a model program to its customers, but each truck is tailored according to the customer's specification as a result of the principle of modularization. On a high level, the vehicles can be divided into articulated (tractors) and basic (rigids). Both a rigid vehicle and a tractor can pull one or more trailers connected via joints, which adds to the complexity of the vehicle's dynamics. On European roads the truck and trailer combinations are summarized in Figure 5, but other combinations and lengths exist for certain applications and under certain conditions. Scania offers trucks for a wide range of applications, such as mining, construction, distribution, long haulage and forestry, but the vehicles may also be highly customized for niche applications. Sensitive equipment that needs extra protection may today be placed inside the driver's cab. In the context of high-precision positioning, it should be noted that the cab is connected to the chassis via a separate suspension system, thus introducing potentially non-negligible relative movements between the cab and chassis.

Buses

Typically operating in urban and suburban environments. The buses may be rigid or articulated but do in general not pull a separate trailer. The buses may operate in densely populated areas and may carry more than 50 people at any given moment.

Coaches

Primarily long distance, intercity applications. Scania manufactures complete coaches but supplies the engine and chassis to bodybuilders to build upon too.

6.1.5 Scenarios

This section describes the scenarios in more detail using a standardized set of descriptors. For live testing the AstaZero testing ground shall be used. However, data gathered during live trials shall be able to be replayed and affected in order to simulate test cases not producible in the AstaZero environment.

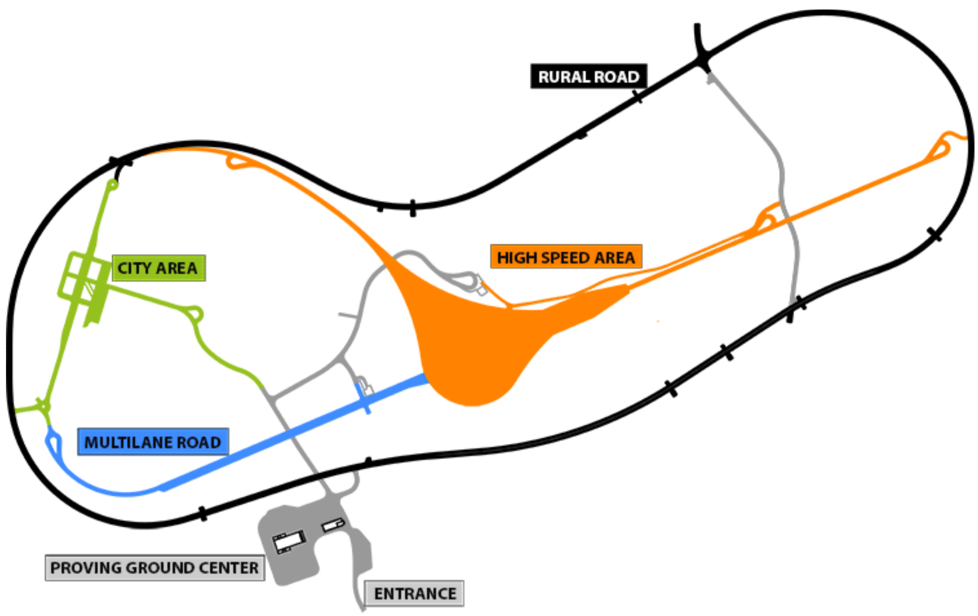


Figure 6 AstaZero map

6.1.5.1 Motor Way

This scenario is intended to recreate driving conditions for a transport vehicle travelling on a motorway.

Criteria	Description
Platform	Einride POD
Target test area	AstaZero multilane road
Speed	Constant velocity 80 km/h
Turns	Straight Line
GNSS environment	Open sky with intermittent limited outages, maximum 30 meters
Assumed mask angle	5 degrees
Signal distortion	none
GNSS Reference Network Configuration	as per SWEPOS current installed base, and grid VRS structure
Cellular Network configuration	as per AstaZero configuration

Table 2 Motorway test definition

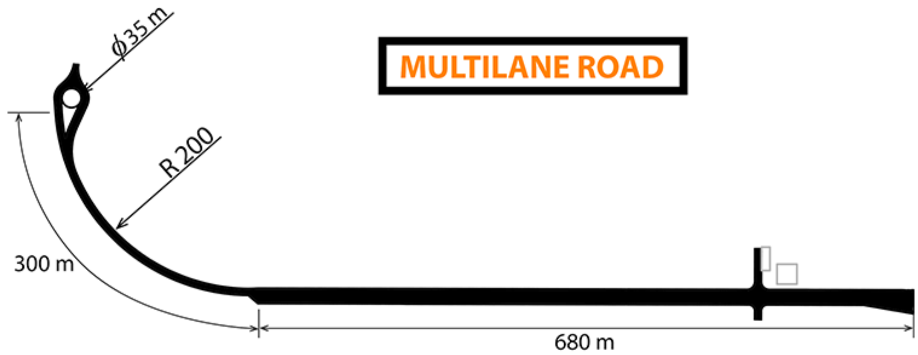


Figure 7 AstaZero Multilane

6.1.5.2 Rural Road

This scenario is intended to recreate driving conditions for a transport vehicle travelling on a single lane major road.

Criteria	Description
Platform	Einride POD
Target test area	AstaZero rural road
Speed	varying velocity, max 60 km/h
Turns	Shallow
GNSS environment	Open sky with foliage of varying height and density on either side of the road
Assumed mask angle	5-30 degrees, foliage dependent
Signal distortion	attenuation, scattering, rapid fading for low elevation signals
GNSS Reference Network Configuration	as per SWEPOS current installed base but grid VRS adapted to force a reference station handover
Cellular Network configuration	as per AstaZero configuration but with forced base station handover

Table 3 Rural road test definition

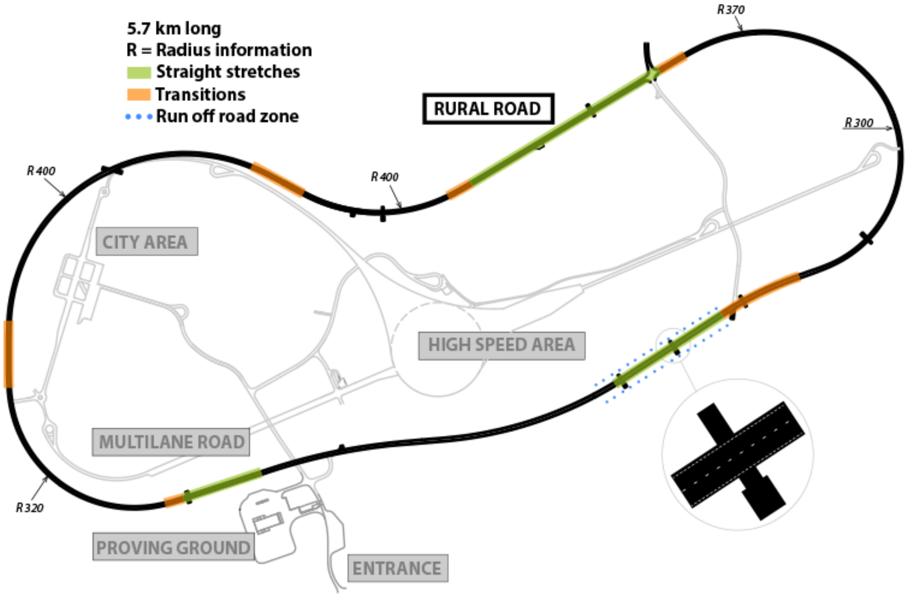


Figure 8 AstaZero Rural Road

6.1.5.3 Coastal Road

This scenario is intended to recreate driving conditions for a transport vehicle travelling on a single lane major road, but near the coast. This is to exercise performance near the edge of the GNSS reference network coverage. It has the same configuration as Rural Road with the exception that the GNSS Reference Network is adapted to only use physical reference stations on one side of the vehicle. The reference station should be excluded to the East or West of the test site to best represent coastal driving.

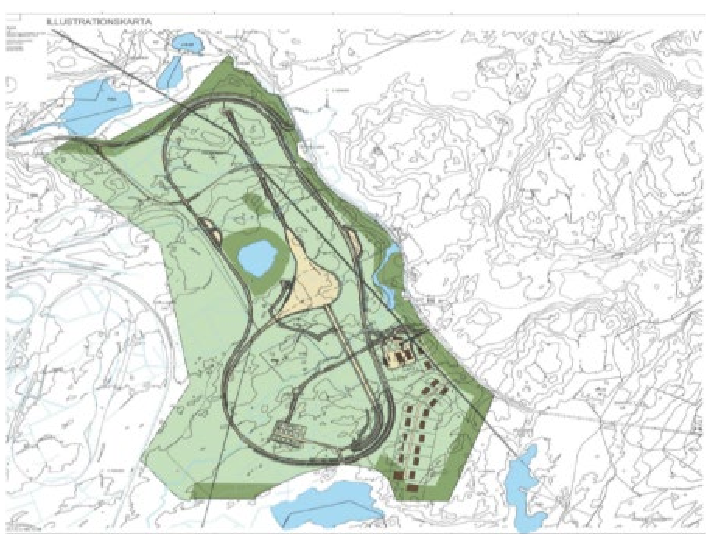


Figure 9 AstaZero map, georeferenced

6.1.5.4 Transport Hub

This scenario is intended to recreate driving conditions for a transport vehicle travelling in a transport hub such as a port, airport or depot.

Criteria	Description
Platform	Einride POD
Target test area	AstaZero city area
Speed	varying velocity, max 40 km/h
Turns	Steep, including right angles
GNSS environment	Open sky with buildings on either side of the road.
Assumed mask angle	5-30 degrees, building dependent
Signal distortion	Multipath and signal blocking
GNSS Reference Network Configuration	as per SWEPOS current installed base.
Cellular Network configuration	as per AstaZero configuration

Table 4 Transport Hub test definition

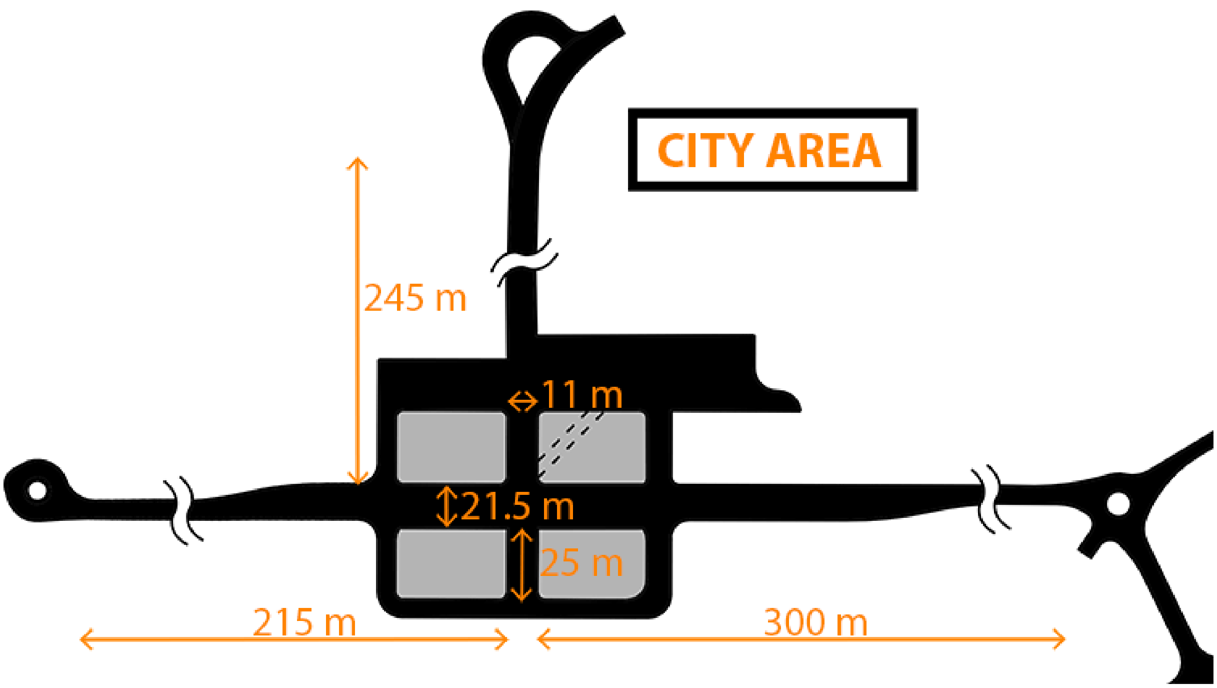


Figure 10 AstaZero City Area

6.1.5.5 Ad hoc

Due to the nature of ad hoc testing, it cannot and should not be planned, but it is acknowledged here that the scenarios described may not constitute the complete set of tests carried out.

6.1.6 Key System Requirements

The Use cases, Environment and dynamics bounding the requirements are covered in previous sections. This section will cover the requirements appropriate for those scenarios.

6.1.6.1 Functional

Network

- The correction service shall be available 24/7.
- The service shall be available in Södertälje (Scania's test track and parts of E4 and E20). If possible, the service shall be available on a coastal road (or simulated coastal road) in order to evaluate effects of one-sided (physical) base station coverage.
- The correction service shall be available scale globally.
- Correction data should include indicators of accuracy and integrity. This could be contained in the residuals message but may need to be more specific for VRS grid/broadcast use cases. Integrity of the navigation solution will also be driven by satellite, Inertial and other sensor data input quality and integrity.
- The grid should be made up of equilateral triangles with spacing of 16 km between VRSs to maintain at most 10 km distance from any VRS at any time.
- Handover between VRSs should be seamless, even across borders and between different reference systems.
- The system should be able to handle several users simultaneously, 100+ clients

Vehicle

- The positioning system shall provide timestamped position, velocity, attitude and heading (navigation data).
- The navigation data shall be provided at 100 Hz, RTK position at 10 Hz.
- The timestamp shall be relative to a shared global time reference.
- The timestamp shall be accurate to 50 ns.
- The navigation data shall have a maximum latency of (500) ms. The navigation data should be compensated for latency.
- Raw GNSS data should be available
- The navigation data should be available independent of weather
- The navigation data should be accurate for any type of motion, for example Short and abrupt maneuvers
- The navigation data should be correct independent of speed of the vehicle
- The navigation data cannot degrade more than a factor 10 with partially obscured view of the satellites
- Heading data should be accurate to 0.1 degree.
- RTK should be available 95 % of the time in the transport hub scenario.
- Signals indicative of accuracy confidence shall be provided. The format shall either be expressed as estimated error interval in meters; or in a format that can be converted into an estimated error interval in meters in a later step. In the latter case information shall also be provided on how to make the conversion.

6.1.6.2 Performance

- The time to ambiguity resolved fix (TTARF) should be lower than 10 seconds in open sky conditions, assuming hot start conditions.
- The time to ambiguity resolved fix (TTARF) when transitioning from the complete loss of carrier phase tracking of every satellite to open sky conditions:
    - Reacquisition of ambiguity resolved fixes shall be within 2 seconds when the rover position is known to better than 0.5m max error 3D in open sky conditions.
    - Reacquisition of ambiguity resolved fixes shall be within 10 seconds when position is known to worse than 0.5m max error 3D in open sky conditions.
- In open sky conditions the position shall be accurate to 3cm 1 sigma assuming a normal distribution.
- In open sky conditions, the position shall be 100% available after first fix.
- The positioning system shall have a protection level of 20 cm, maximum.
- The positioning system's target integrity risk shall be 1e-12, maximum.
- The positioning system shall be well tuned, and the confidence shall represent the error over a large population.
- The warm-up and initialization time shall be about 10s of seconds or less.
- The positioning system must not require any start-up sequence.

6.1.6.3 Electrical/Physical/Data

Network

- The network shall deliver GNSS correction data in line with 3GPP standards.
- Redundancies all along the supply chain should be put in place to create a fail-safe system
- Well defined interfaces for the entire correction supply chain should be in place

Vehicle

- The positioning device shall operate from 12 volts.
- The positioning device, except for the GNSS antenna, shall be hard mounted to the Chassis of the vehicle with the option for damping depending on vibration.
- The GNSS antenna shall be installed on the roof of the vehicle.

6.1.6.4 Legal, Financial and Certification

Given the complexity of the complete system, the legal, financial and certification requirements shall be considered at the sub system level.

Network

- A business model proposal for the distribution of corrections to fleets of trucks and/or companies should be in place

Vehicle

- The cost of the positioning system shall be similar to mass market GNSS receivers
- The positioning system shall not be bound by export restrictions.
- The positioning system shall have an ASIL certification.

6.1.7 Testing requirements

6.1.7.1 Network

- The correction service shall be possible to test in a simulation environment with hardware in the loop.

6.1.8 Note on integrity

GNSS positioning cannot operate in all the environments specified, so specifying an accuracy requirement is not appropriate. When a system can have varying accuracy, an uncertainty should be provided with the estimate. How well this uncertainty models the actual error is integrity. Individual estimates cannot be compared in isolation but should be compared as part of a larger statistical population to determine whether the modelling of a data set is accurate when considered as a population. The impact of a false negative, where the system estimates a large uncertainty, but the error is actually very small is quite possible as part of a statistical distribution and would make the system potentially inefficient should it occur more frequently than the probability distribution would dictate.

The impact of a false positive, where the system estimates a small uncertainty, but the error is actually very large has a direct impact of the safety of the system. The size of the actual error will affect the safety of operation of the vehicle. The consumer of the positioning estimate will need to consider the uncertainty in line with the safe operating conditions of its current situation. The positioning system has the responsibility to provide accurate uncertainty estimates which reasonably model the errors over large data sets. The consumer has the responsibility to maintain safe operation given the uncertainties, and other sensors available to corroborate or contradict the GNSS positioning.

6.1.9 Note on latency

Latency can be broken down into 2 aspects: a delay between the actual motion event happening and the data being timestamped, and then the delay between the timestamped motion data being processed and available to a subscriber. The former could be compensated but is highly sensor dependent and could have noise/jitter in the latency. The latter is known latency which can be managed by propagation of the data forwards/ backwards to a suitable time. The software provides an interface which allows the user to request a navigation solution at a specific time, and the software interpolates/extrapolates the solution to the requested time and provides an appropriate uncertainty.

6.1.10 Positioning Requirements for mass market applications

Today, over 5 billion GNSS devices are in use around the world, 80% of which are smartphones [7]. Many Smartphone applications are getting closer to the border of safety-critical or high precision ones. The potentially higher location accuracy that can be obtained in the mass market will further increase the use of smartphones and wearables in semi-professional applications and enable a new range of consumer applications that are still not possible today. The typical performance of today's mass market mobile devices is in the range of meters to even tens of meters in difficult conditions, such as urban canyons. However, the use of multi-constellation, dual-frequency chipsets and the provision of external information promise to increase this accuracy to sub-meter levels in the near future. Modern mobile phones, deploying system on chip, are more capable than the mainframe computers of 20 years ago. This results in lower costs for deploying and testing new applications with quicker update cycles and without the burden of having to develop hardware. Android raw measurements will provide additional layers of integrity and robust position, enabling the development of robust, reliable and interference-resilient position-based services. Many mass market applications can benefit from increased accuracy. A list of examples can be found in

Figure 11 Smartphone applications utilizing higher location accuracy [7]

6.2 Network RTK, SWEPOS, Caster

6.2.1 Introduction to SWEPOS

SWEPOS is the national CORS network of Sweden operated by Lantmäteriet. The first stages of this geodetic infrastructure were established in the early 1990s. Operation, maintenance and development of SWEPOS are presently the responsibilities of Lantmäteriet (the Swedish Mapping, Cadastral and Land registration authority). The Swedish GNSS reference station network has been developed in different stages to be able to meet the requests on better positioning uncertainty, reliability and availability. In general, SWEPOS is based on:

- Physical infrastructure, consisting of the permanent stations and hardware of the control center;
- Transmission infrastructure capable of transmitting real-time data flow from the stations to the control center and from this to the user according to own protocols or standard one;
- Computing infrastructure, consisting of the software Trimble Pivot Platform (TPP) that can improve the estimation of the various errors and make them accessible to users spread over the territory.

The present SWEPOS Network-RTK Service is based on the Virtual Reference Station (VRS) concept, with two-way mobile network communication between the control center and the RTK users. The network computing center is located in Lantmäteriet (Gävle) and it generally perform the following steps:

- Determine various errors of different origin, including atmospheric errors, clock errors, and local multipath with cm-accuracy by fixing the ambiguities of the baselines within the network,
- Simulate the position of the VRS by geometrically displacing the data of the reference station closest to the rover,
- Interpolate the network errors at the VRS location using linear or more sophisticated models,
- Transmit the corrections to the rover in real-time.

Lantmäteriet is offering several services based on the data from the reference station network:

- Quality checked RINEX data through http/ftp
- A web-based automatic computation service (cm level post-processing)
- A DGNSS service (open data).
- Network-RTK and Network-DGNSS services (cm level and dm-level in real-time)

The present SWEPOS infrastructure consists of approximately 450 permanent GNSS reference stations located as shown in Figure 12. The distances between these stations can be classified into the following configurations [11].

- **Normal Configuration (ND):** It’s the original form of SWEPOS NRTK which was built through establishing NRTK service in 2002-2010. The distances between the stations are 70 km.

- **Densified Configuration (DC):** It's the densified form of NRTK service. The distances between the stations are 35 km. The densification from 70 to 35 started in 2010 for improving the network performance.
- **High-Densified Configuration (HDC):** It's a special form of NRTK service and implemented for the areas that need very high performance (project-oriented positioning services). The distances between the stations are 10 km.

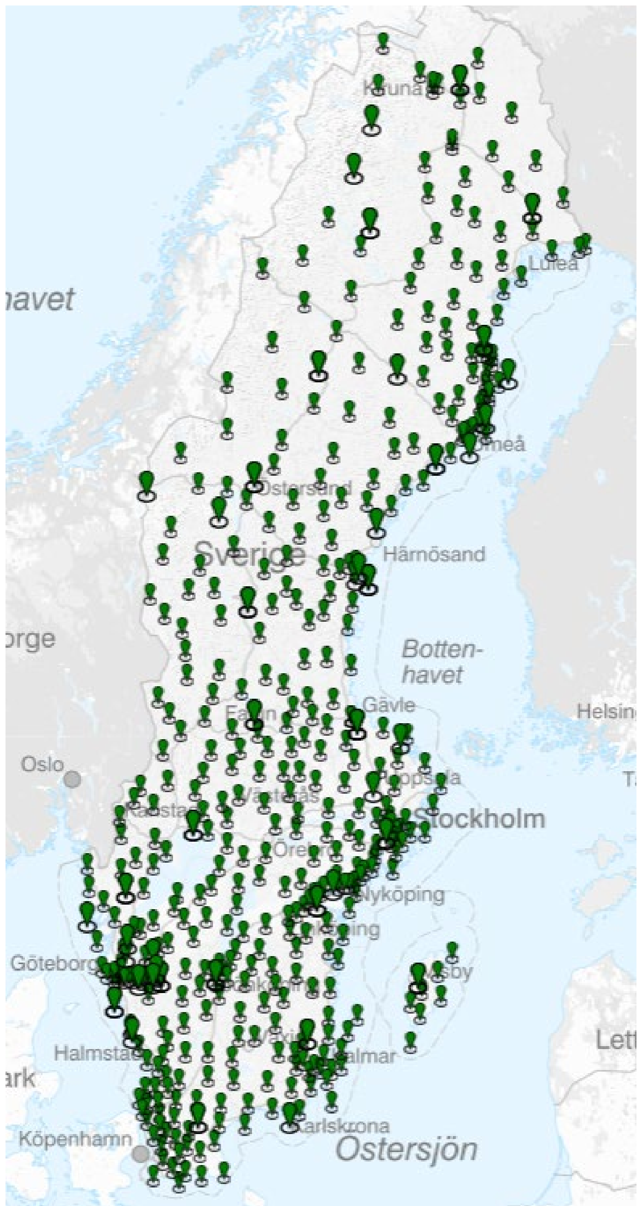


Figure 12 Map of SWEPOS reference stations.

All SWEPOS stations are equipped with very modern GNSS receivers which can receive and process the signals/frequencies from all current GNSS constellations (GPS, GLONASS, Galileo, Beidou, …). Figure 13 shows two types of GNSS receivers (Trimble Alloy and Septentrio PolaRx5) which are the most common types on the SWEPOS stations. Data is collected every second and a 5 degrees elevation mask (in data processing software) is used. The GNSS antenna at every station is a choke-ring antenna of Dorne Margolin design mounted under a radome. The radomes are made of clear acrylic.

Figure 13 GNSS receivers used in most of SWEPOS stations

In general, SWEPOS has two types of reference stations: Class A stations and Class B stations [11]. The Class A stations have the best long-term coordinate stability because the GNSS antennas are mounted on insulated concrete pillars or truss masts with fixed anchorage in crack-free bedrock. Other equipment at the stations is installed in some type of technology shed. There is good redundancy for GNSS measurement, data communication and power supply, i.e. reserve capacity that can be activated in the event of a problem. The Class A stations include the 21 so-called fundamental stations which comprise the physical backbone for the Swedish national reference frame system SWEREF 99. The Class A stations are also used to monitor the coordinate stability of the Class B stations. Figure 14 shows an example of the class A station.

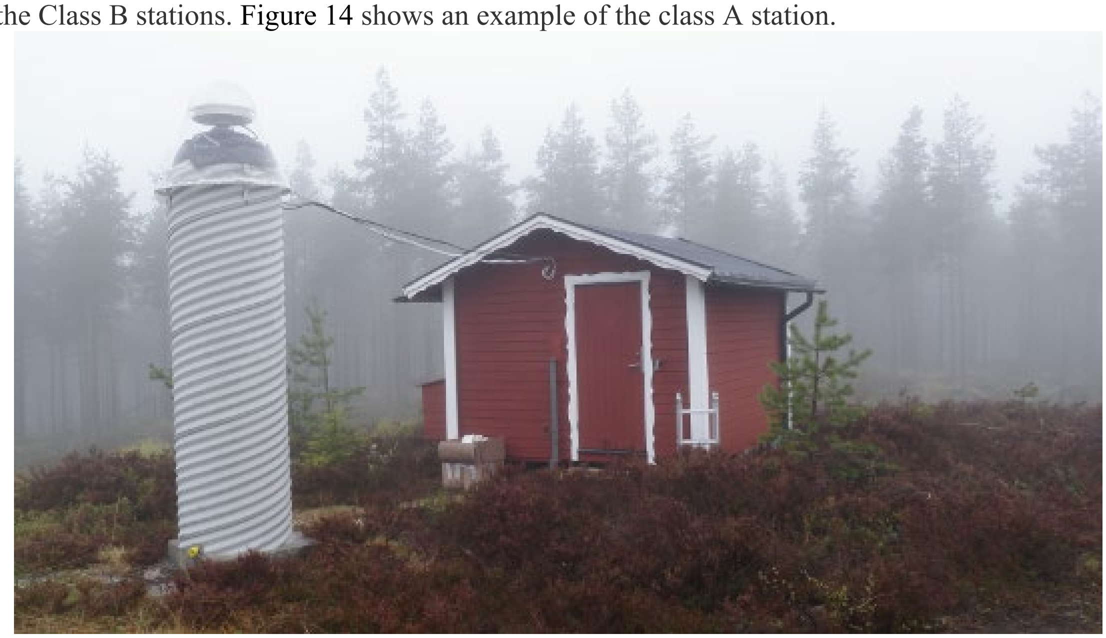


Figure 14 Class A station Leksand.

The Class B stations are densifying the network of Class A stations in the expansion of the SWEPOS network that is being done to increase the capacity for real-time measurement. Therefore, the Class B station is the most common type of station (approximately 90% of the SWEPOS network). The Class B stations have GNSS antennas that are roof mounted on buildings (as shown in Figure 15) and do not have the same redundancy as the Class A stations, in terms of equipment. The coordinates of the stations are checked by daily calculations, e.g. to detect any movements.

Figure 15 Storuman, a class B station with a ceiling-mounted antenna.

6.2.1.1 Communication standards used in SWEPOS

The transmission infrastructure is a very important part in Network-RTK. It should be capable of transmitting a real-time data flow from the stations to the control center, and from the center to the ship according to own protocols or standard one.

To allow for the real time transmission of Differential Global Navigation Satellite Systems data DGNSS, the Radio Technical Commission for Maritime Services (RTCM) Special Committee 104 developed the RTCM format. RTCM was formed as a United States government advisory committee in 1947. Currently, RTCM is an international scientific, professional and educational organization that is supported by its members from all over the world. The special committee 104 is a group of government and non-government members started work together in the year 1983 on different tasks to develop technical standards and consensus recommendations for transmitting different corrections to GPS users. In 1985, draft recommendations were published, followed by a series of updated versions.

RTCM version 3.x was designed to be more efficient than the earlier RTCM versions. It was a completely new standard with new message types and a new structure. The format RTCM version 3.x was enhanced with the addition of a NRTK correction message types and supports GPS and GLONASS RTK operations. Message types in these versions have been structured in different groups. For proper operation, the provider must transmit at least one message type from each of the following groups:

- Observations,
- Station Coordinates, and
- Antenna Description

More recently, the standard has been modernized with the Multiple Signals Messages (MSM) record type that allows for the generic inclusion of new constellations and signals. MSM currently supports GPS, GLONASS, Galileo, BDS and SBAS. Additional information on the RTCM standards can be found in [12]. In NPAD project, SWEPOS will transmit the N-RTK corrections (VRS solution) to the ship encoded in the message's types shown in Table 5.

Table 5 RTCM messages used in Prepare-ships project

	Msg #	Message name & description
1	1005	Stationary RTK Reference Station ARP
2	1032	Physical Reference Station Position
3	1033	Receiver and Antenna Descriptors
4	1074	GPS MSM4
5	1084	GLONASS MSM4
6	1094	Galileo MSM4
7	1230	GLONASS L1 and L2 Code-Phase Biases
8	1030	GPS Network RTK Residual Message
9	1031	GLONASS Network RTK Residual

Structure of the correction data used in NPAD project contained the correction information for the three GNSS constellation: GPS (GPS), GLONASS (GLO) and Galileo (GAL). RTCM MSM 4 has been used in the data streams by using the messages 1005, 1006, 1007, 1008, 1032, 1033 at the frequencies shown in

		GNSS Systems			RTCM 3 Message Periods (≈s)												
Mountpoint	Format	GPS	GLO	GAL	1004	1005	1007	1012	1030	1031	1032	1033	1074	1084	1094	1230	4094
MSM_GNSS	RTCM3.2	1	1	1	-	5	5	-	8	8	10	5	1	1	1	4	2

Figure 16 Structure of the SWEPOS correction data

In order to achieve comparable performance to VRS, the RTCM network solution generally requires a 1 Hz update rate for the network corrections, although the geometric corrections can be transmitted at a lower update rate.

The data transmission from the reference stations to the control center server and from the control center server to the user for RTK corrections is mostly carried out via the Network Transport of RTCM via Internet Protocol (NTRIP). NTRIP is used for an application-level protocol streaming GNSS data over the internet, allowing simultaneous PC, Laptop, PDA, or receiver connections to a broadcasting host. NTRIP supports wireless Internet access through Mobile IP Networks like Global System for Mobile Communication (GSM). General Packet Radio Services (GPRS), Enhanced Data rates for GSM Evolution (EDGE), or Universal Mobile Telecommunication Service (UMTS).

This NTRIP system consists of the following elements (see Figure 17):

- NTRIP Sources, which generate data streams at a specific location,
- NTRIP Caster, the major system component, and
- NTRIP Clients, which finally access data streams of desired NTRIP Sources on the NTRIP Caster.

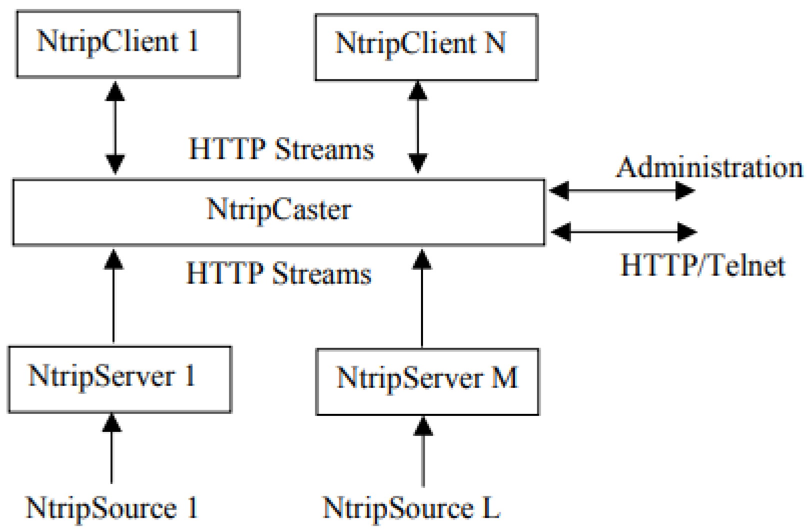


Figure 17 NTRIP Streaming System.

The management is implemented in terms of mount points, port number, password and username, *etc.*, The NTRIP Client receives streaming RTCM data from the NTRIP Caster to apply as real-time corrections to a roving GNSS receiver.

6.2.2 SWEPOS correction service for the mass market applications

In network-RTK, or generally in high accuracy real time positioning services, the reliable and high-speed server-rover communication link (i.e. correction dissemination techniques) plays an important role in the final performance. The traditional way for distribution SWPOS correction data follows the traditional approach to supply a correction data stream via internet as discussed earlier in the report, served in accordance to the NTRIP protocol from a NTRIP Caster. The NTRIP protocol provides the ability for a GNSS correction data user to choose from several available correction data streams from the casters available so-called mountpoints. SWEPOS provide the users with the mountpoint name and a password to enable the user connection to the SWEPOS correction service as shown in Figure 18.

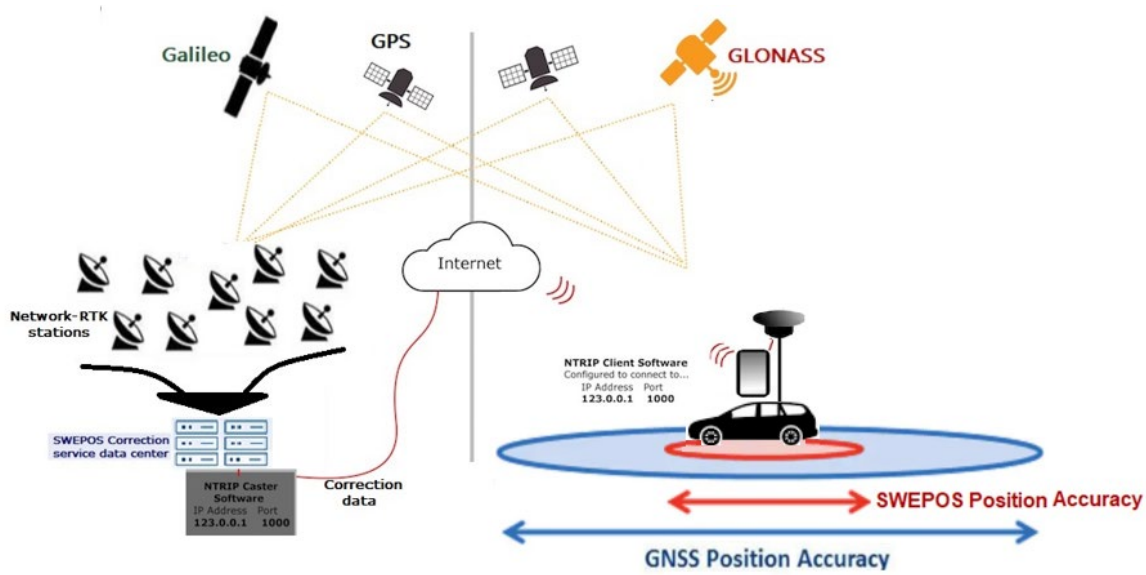


Figure 18 Dissemination of GNSS correction data via internet and NTRIP.

In the traditional VRS approaches, pseudo-range and carrier phase observations which comes from the reference stations are continuously collected and processed by a processing (control) center. The ambiguity of carrier phase value of each individual baseline in control center's online resolving GPS reference station net; Data processing center utilizes the two difference composition errors on every baseline of reference station net carrier phase observation data calculating, and sets up the spatial parameter model apart from correlated error in view of the above; The rough coordinates of the National Marine Electronics Association NMEA form that the movement station user will obtain by single-point location sends to control center, and a virtual reference station (VRS) is created at this coordinate position by control center. At this point the control center will interpolate these values in the virtual reference station location and can generate a set of GNSS observations and corrections calculated as if they were acquired by a hypothetical receiver station in place in that position, obtaining what you could call a "virtual station" or virtual reference station. If it is generated in the position of the rover carries with it a baseline length of almost nothing, resulting in elimination of errors that are spatially correlated.
To determine where to place the virtual station as we talked before, the communication must be bi-directional (as shown in Figure 19) in that the car must make its position known to the processing center that carries out the calculation, sending your location via the NMEA format. This position can be "improved" with the reception of the first differential corrections and re-sent back to the processing center. When the position of the virtual station has been defined, the GNSS differential corrections are continuously transmitted using the RTCM protocol.

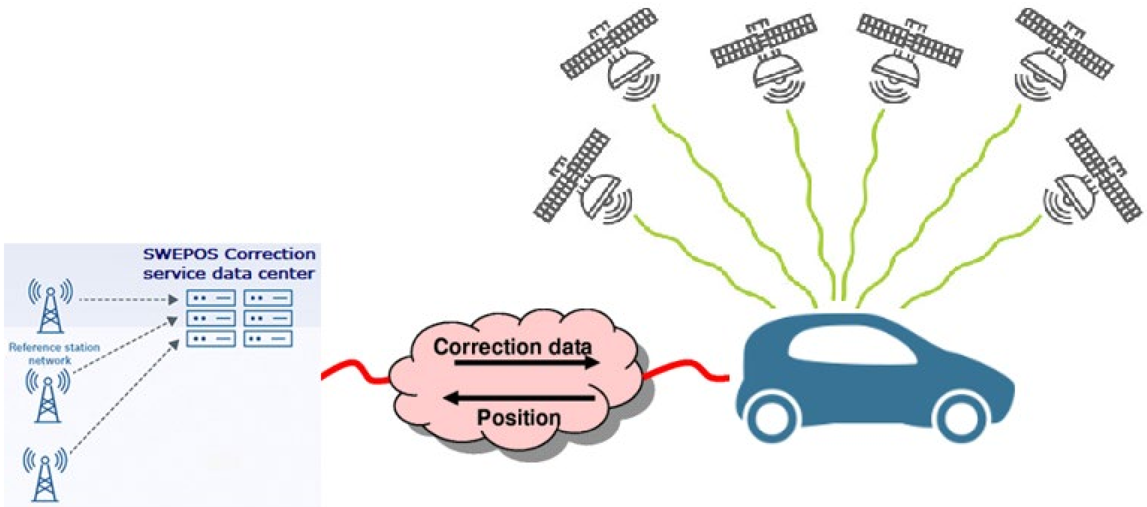


Figure 19 Bi-directional mode used in the traditional SWEPOS technique (VRS).

Furthermore, the bi-directional mode used in the VRS technique is limited by the ability of the processing center to simultaneously perform calculations for all users. As this number grows (mass-market applications, as in the NPAD application), there will be an extensive exchange of messages between the devices and SWEPOS server (see Figure 20), which both can result in a significant load of the communication links causing delays in the provisioning of the corrections. Furthermore, the NRTK server will face challenges processing all the requests and calculating the appropriate correction data adopted for each device.

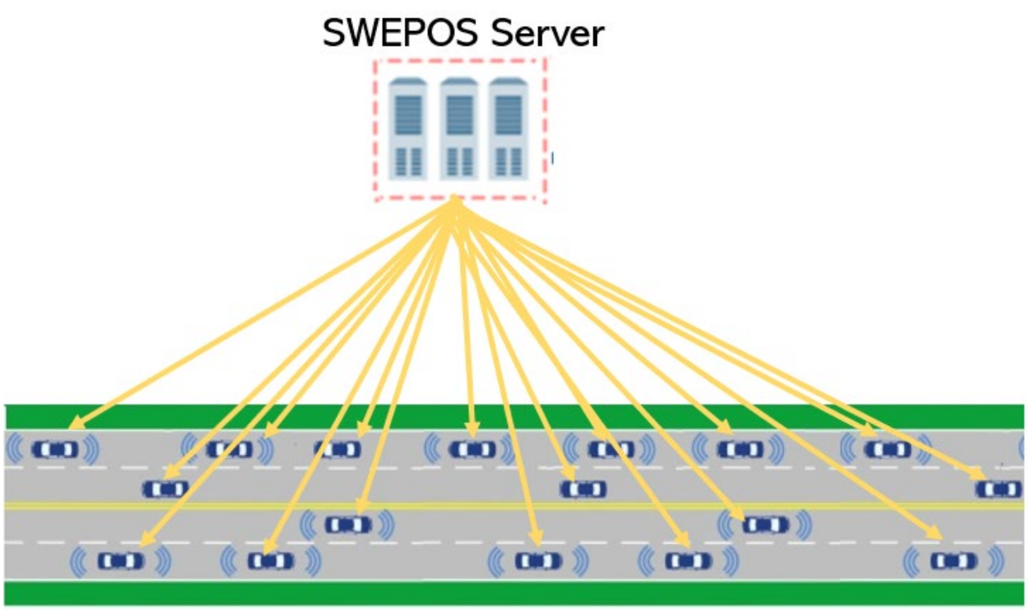


Figure 20 Extensive exchange of messages between the devices and the NRTK server.

The proposed idea in NPAD project depends on using a grid of fixed VRSs which could be established to cover the required area or a specific area (test area in NPAD project as example).

The correction data from SWPOS will provided then from this grid in broadcast mode as shown in Figure 21.

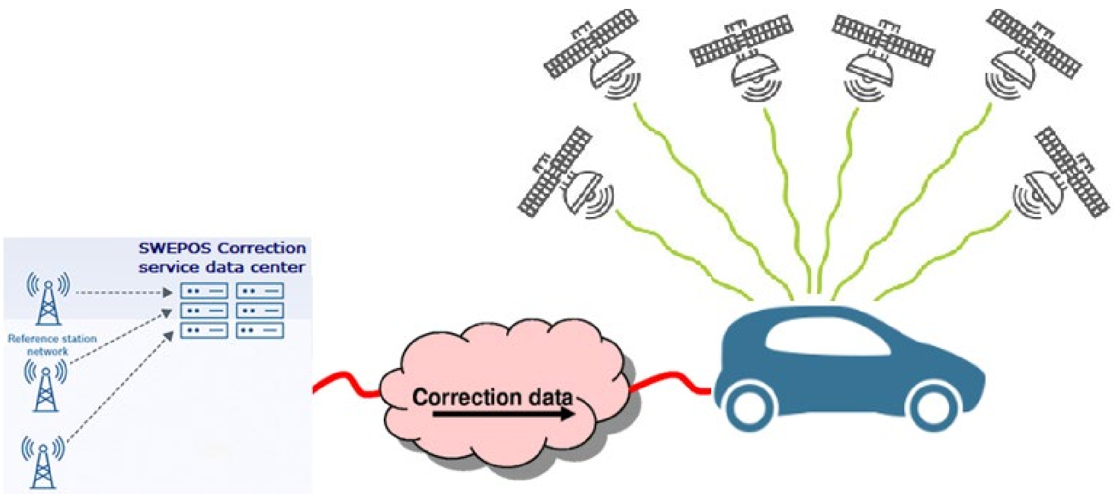


Figure 21 Broadcast mode used in the proposed NPAD service.

In order to implement the ideas proposed in NPAD project, SWEPOS made a proposal to set up a new NTRIP Caster (we will call it '*NPAD'* caster) on a server between the SWEPOS VRS NTRIP casters (the current distribution system of correction data from SWEPOS) and the location server (manages by Ericsson in NPAD project) as is shown in Figure 22.

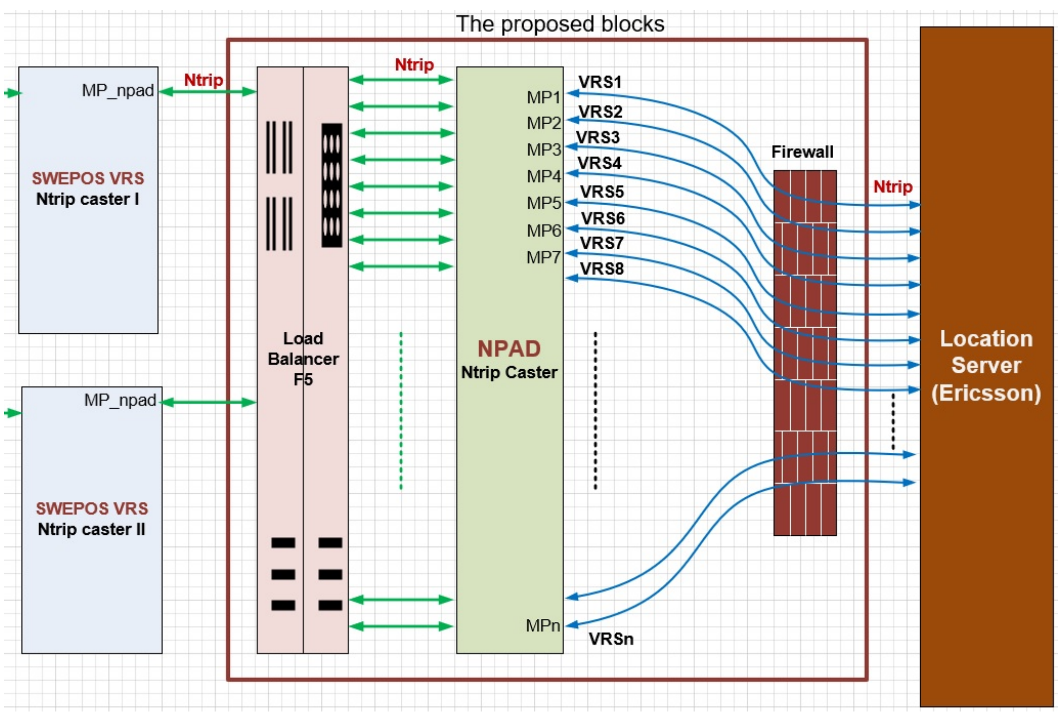


Figure 22 SWEPOS proposed architecture data streams in NPAD project.

On NPAD caster, the required mountpoints (for the proposed VRS grid) can be created to rebroadcast SWEPOS VRS's correction data to the location Server. These mountpoints will send NMEA GGA sentences (with static position) to the SWEPOS VRS casters. The SWEPOS networking software (TPP) will generate VRS data streams for these static positions and deliver them to the NPAD caster. The NPAD caster would then rebroadcast these VRS data streams to the location server without a need for user NMEA input from the location Server (from the VRSs grid). The proposed plan for this NPAD Caster is that it will used for mass usage such that it will support more than thousands of data streams and has minimal latency. A load balancer will be used to distribute the load on SWEPOS VRS casters. Based on that, the corrections for the all VRS's will be send to the locations server which will take the rule to distribute them through the mobile network to the cars as shown in Figure 23.

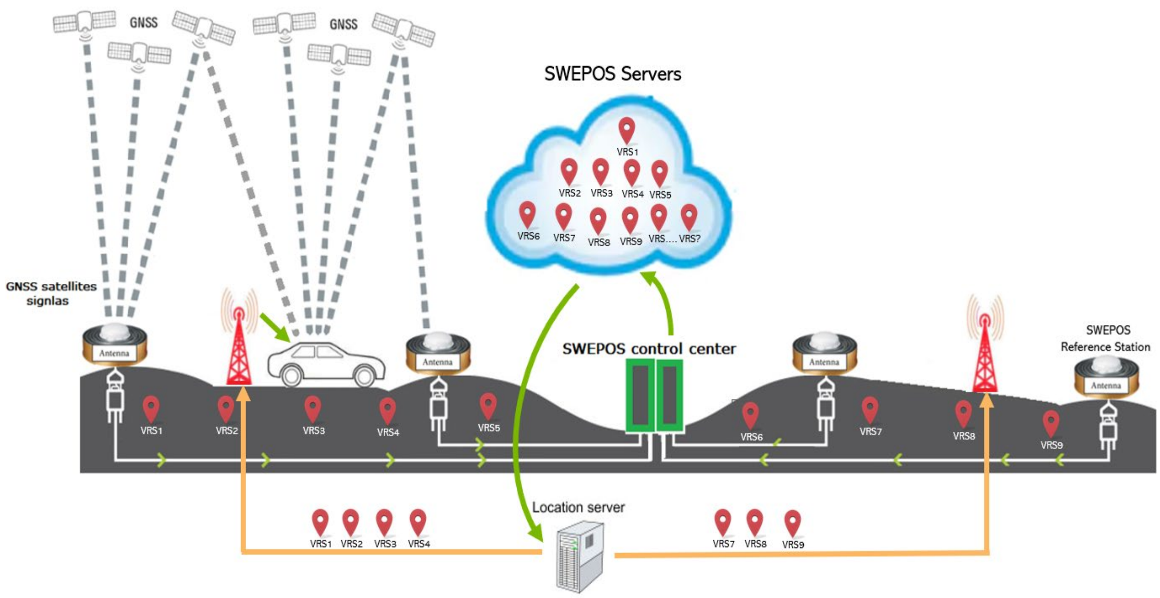


Figure 23 The proposed architecture of distribution SWEPOS correction data in NPAD.

Based on that, several VRS grids have been implemented on the NPAD caster (the new caster) for testing and verification. Figure 24 shows an example of these grids, one grid in AstaZero (it contains four VRSs: Asta1, Asta2, Asta3 and Asta4) and other one on RV40 road between Borås and Gothenburg (it contains ten VRSs: RV4001, RV4002, RV4003, RV4004, RV4005, RV4006, RV4007, RV4008, RV4009 and RV4010).

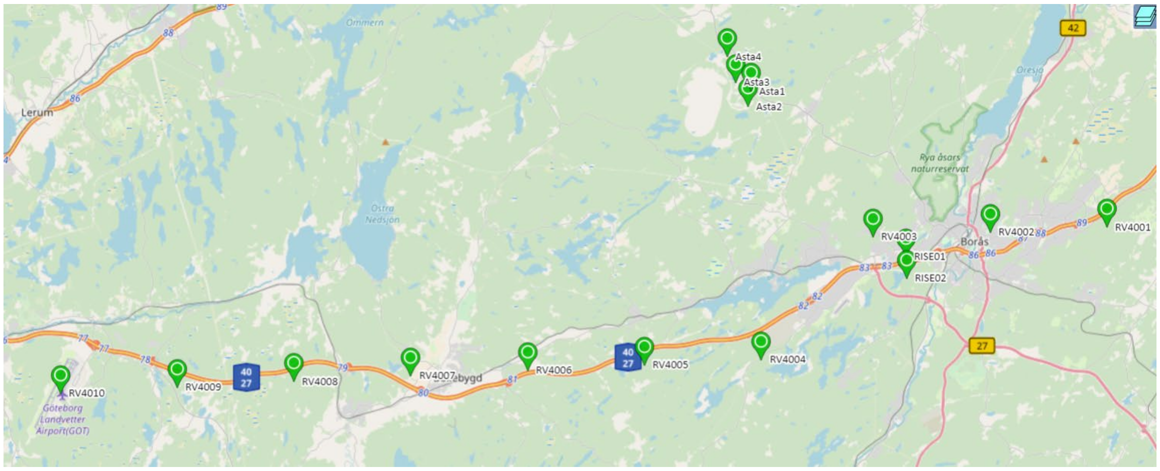


Figure 24 Two grids implemented on the NPAD caster

Lantmäteriet made several static tests during the work in the NPAD project to prove the concept of the proposed NPAD. The testing procedures have been performed in corporation with RISE and the tests was done at RISE office in Borås. Two U-box receivers (Ublox1 and Ublox2 in the Figure 25) connected to the same antenna (Leica AR25 Choke Ring), the Ublox1 has been connected to SWEPOS service directly (traditional SWEPOS service) and the Ublox2 has been connected to NPAD testing equipment's. To study effect of the distance between the VRS and the GNSS receiver on the car, the VRS for Ublox2 has been changed as is shown in Figure 25.

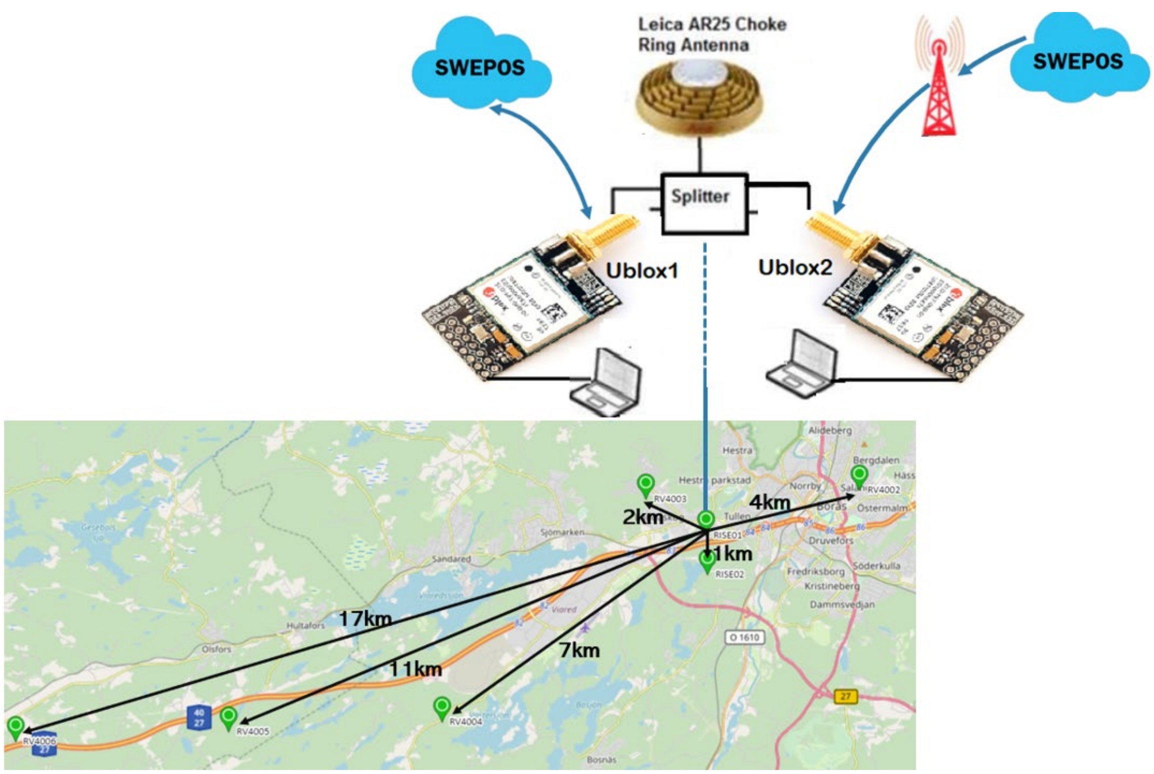


Figure 25 Lantmäteriet test scenarios in NPAD project.

Seven VRSs have been used in the testing procedures. Table 6 The VRSs list used in testing shows the list of these stations with their distances from the antenna (point of the testing).

Table 6 The VRSs list used in testing

VRS's name	Distance
RISE01	10 m
RISE02	1km
RV4003	2 km
RV4001	4km
RV4004	7km
RV4005	11km
RV4006	17km

Table 7 shows the horizonal RMS and vertical RMS for the two test scenarios (two receivers) with different time (different correction VRS source). The results have proved that the NPAD solution can provide the same accuracy as of SWEPOS traditional service when the car is near to the VRS. On the other hand, the initial results showed that the acceptable distance to the VRS is less than around 7 km, but more tests are necessary. Several other parameters (such that ambiguity resolution success rates as example) should also be taken into consideration to verify this result. This is needed to evaluate the optimum distances between the VRSs in the grid.

		Ublox RX1		Ublox RX2		
		H-RMS error (m)	V-RMS error (m)	VRS	H-RMS error (m)	V-RMS error (m)
12/11/2020	24 h	0.057	0.165	RISE01	0.054	0.166
13/11/2020	24 h	0.052	0.167	RISE02	0.055	0.165
14/11/2020 18/11/2020	24 h 22 h	0.055 0.056	0.166 0.165	RISE03	0.056 0.057	0.165 0.163
15/11/2020	24 h	0.051	0.167	RV4002	0.056	0.168
16/11/2020 22/11/2020	24 h 6 h	0.053 0.051	0.165 0.166	RV4004	0.060 0.121	0.171 0.170
23/11/2020	6 h			RV4005	0.125	0.172
23/11/2020	6 h			RV4006	0.128	0.164

Table 7 The test results.

6.2.2.1 On Scalability of NPAD Project – SWEPOS side

The design of the virtual grid of reference stations base in the proposed NPAD solution for SWEPOS RTK-Network is one of the most important aspects that has been discussed in NPAD project. One of the main factors in designing the virtual grid is the distance between the VRSs within the grid. Based on the initial results obtained from the NPAD project, the distances between the VRSs in the grid should not exceed 14 km, and in that case the distance between the car and the nearest VRS will be less than or equal to 7 km. Based on that, the proposed configuration of SWEPOS virtual grid will be to use 10 km as a distance between the VRSs (This means that the longest distance between the car and VRS will be around 7 km) as is shown in Figure 26. This configuration should be tested with more factors taken into considerations, such as:

1. Effect of distance between the VRSs on TTFF.
2. Effect of the distance between the VRSs on AR Availability.
3. Effect of the distance between the VRSs on RTK accuracy
4. Effect of the distance between the VRSs on RTK availability
5. The current cellular base stations configuration.

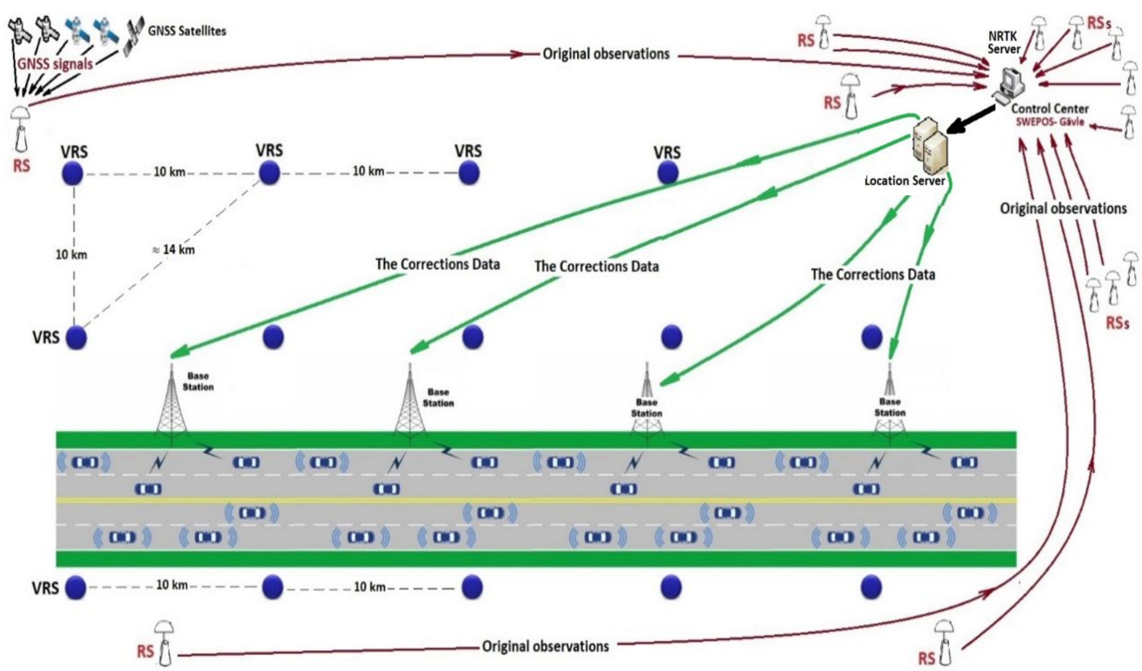


Figure 26 The proposed configuration for NPAD project.

From practical viewpoint, it is possible to change the VRSs intensity and their positions related to different considerations as example the traffic density, population density. In general, we can deploy the VRSs grid based on two main methods:

1. **Road-based coverage.**
   In this method, selection of the VRSs position is based on map of the roads (highways road, rural roads, dirt road, …). Figure 27 shows an example for the road RV40 between Borås and Göteborg and how the VRSs grid can be deployed on the road. The grid includes 10 VRSs (RV4001 – RV4010) deployed with around 10 km distance between the VRSs.

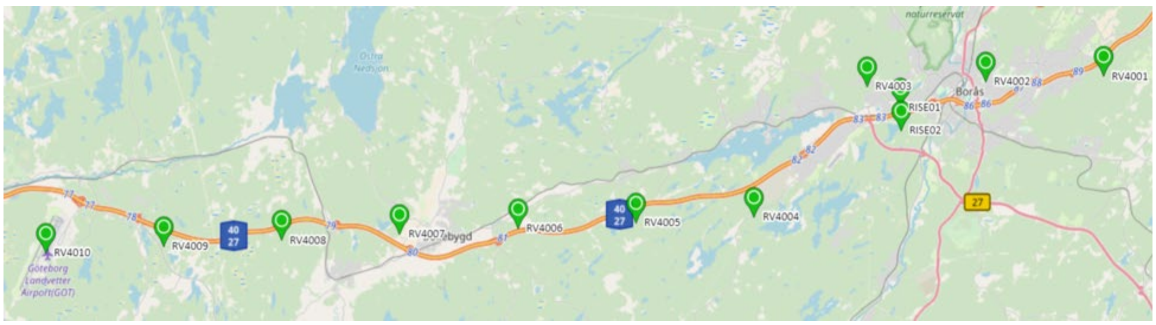


Figure 27 VRSs deployed on the road RV40.

2. **Area-based coverage.**
   In this method, selection of the VRSs position is based on geometrical coverage for the required area. Figure 28 shows an example for the area in Västervik and how the VRSs grid can be deployed in the required area. The grid includes 12 VRSs deployed as a parallelogram (sometimes trapezoidal) with around 10 km distance between the VRSs.

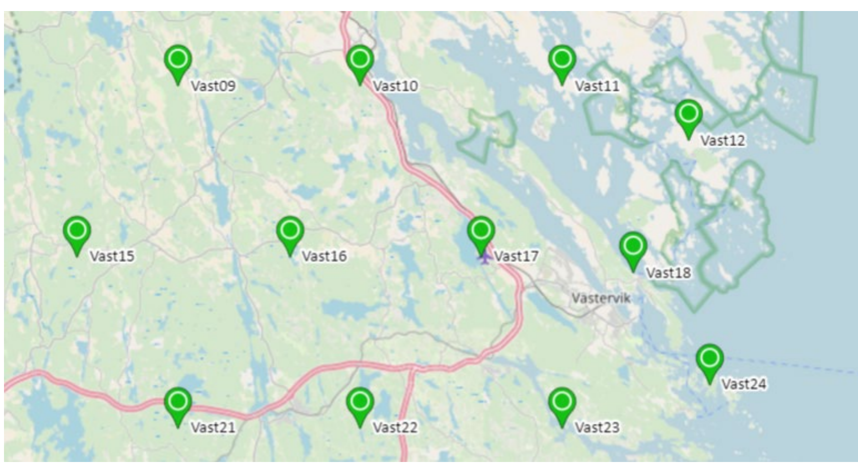


Figure 28 VRSs grid deployed based area coverage.

6.2.2.2 Reliability of SWEPOS high-accuracy correction service

Redundancy is a common approach to improve the reliability and availability of any system. In order to make the proposed SWEPOS distribution system in NPAD more reliable, a redundant processing data center (processing data center 2 in Figure 29) has been built to be used in parallel with the main data center (processing data center 1 which is located physically in Gävle-Lantmäteriet).

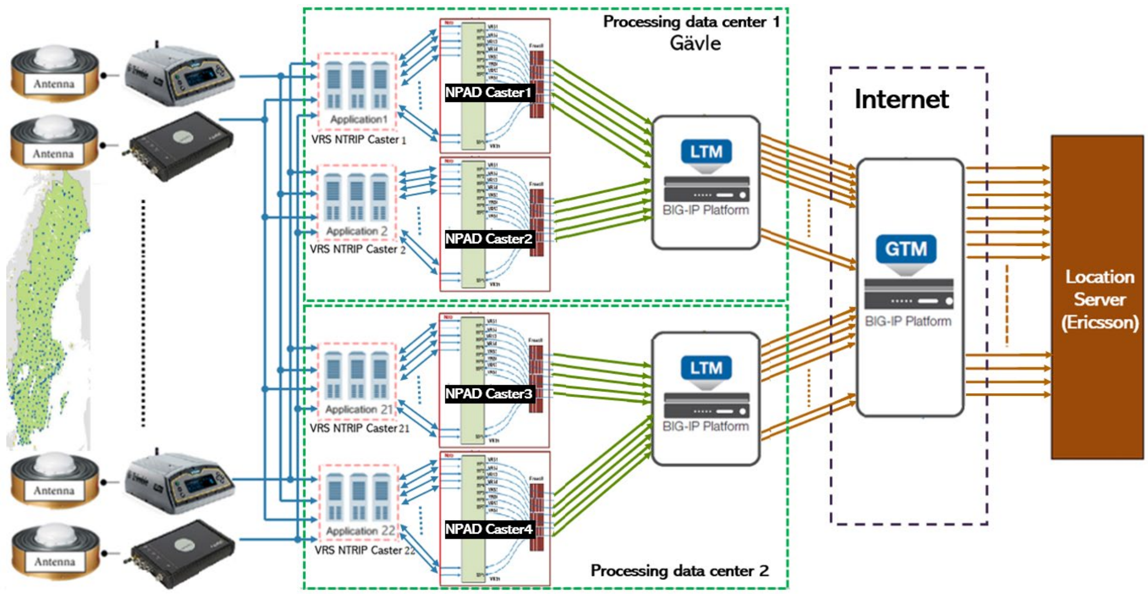


Figure 29 The implemented architecture of SWEPOS NRTK data distribution.

The proposed infrastructure (Figure 29) depends on using the Global Traffic Manager (GMT) which is one of the cutting-edge modules offered on F5 Networks® BIG-IP® platform. "Global" is the right word for this module because it has the ability to make name resolution load balancing decisions for systems located anywhere in Sweden (processing data center 1 and processing data center 2). You can think of the GTM as an intelligent DNS (Domain Name System) that is security minded. In other words, its logic can make informed decisions on correlating a hostname to an IP address while keeping security in check. Most things you do on the Internet or private networks will start with name resolution, so it makes sense if we're going to load balance an application it would start at this layer – resolving names to IPs based on availability, performance, and even persistence. It's important to note, traffic does not "route" through the GTM, the GTM simply tells us the best IP to route to, based on metrics for the URL in question.

On the other hand, the Local Traffic Manager (LTM) can be used to is allowing us to augment client and server-side connections. All while making informed load balancing decisions on availability, performance, and persistence. "Local" in the name is important, opposed to the GTM, traffic actually flows through the LTM to the servers it balances traffic to. Usually the servers it's load balancing sit "locally" in the same data center as the LTM, though that is not a requirement. The main configuration element on an LTM is the Virtual IP or VIP for short. There are several configuration elements that work with VIPs, but at the heart of the technology it's a VIP they are all a part of. Like a WIP, VIPs equate to the URL you're load balancing, but at its lowest level. Like a WIP it usually contains a pool with the servers it's load balancing & monitor(s) to measure availability / performance.

6.3 GNSS Reference Data via 3GPP LPP

6.3.1 Background

Already since GSM, assisted GNSS has supported connected GNSS devices with information corresponding to the navigation message to significantly reduce the time to first fix. In early 2017, 3GPP started the work to include support for GNSS RTK in the assistance data of the LTE Positioning Protocol (LPP) Release 15 [5]. The justification of the work was to ensure a scalable and interoperable GNSS RTK assistance data cellular network distribution to enable mass-market services. Up until then, GNSS RTK was supported using generic cellular connectivity, typically based on RTCM SC 104 [12], which allows proprietary messages, resulting in a not fully open and interoperable distribution system. Furthermore, the assistance service scales badly, with both computations and signaling costs scaling with number of users. In order to open up a large eco system for precise GNSS RTK positioning, a scalable and interoperable distribution is vital.

Leveraged by RTCM SC 104, 3GPP defined procedures and information elements to introduce support for GNSS RTK in LPP Release 15, completed in 2018. Care was taken to define all attributes and only include well-defined pieces of information to ensure full interoperability. GNSS RTK assistance data is often separated into two types of representations:

- Observation Space Representation (OSR). The assistance data consists of precise GNSS signal observations associated to a provided precise coordinate which corresponds to either a physical reference station or a non-physical reference station (sometimes referred to as a virtual reference station (VRS)).
- State Space Representation (SSR). The assistance data consists of GNSS signal observation error contributions from the satellite segment (orbit and clock errors) and the atmospheric segment (ionospheric and tropospheric delay errors).

3GPP LPP Release 15 assistance data includes supports for GNSS RTK OSR and SSR phase 1, with satellite orbit and clock error contributions. The work continued with LPP Release 16 to include complete support also for SSR by adding support for atmospheric spatial delay models and satellite signal phase biases and continues in 3GPP Rel 17 with support for GNSS integrity.

Despite the protocol name, 3GPP LPP supports both 4G/LTE/EPC and 5G/NR/5GC (from Release 15) devices and networks. The work in 3GPP on GNSS RTK is not only about procedures and information representation, but also on architecture and assistance data distribution. Figure 30 illustrates the positioning architecture in 3GPP 4G/LTE/EPC [4], and the architecture is very similar for 5G/NR/5GC. The device (user equipment – UE as well as SUPL Enabled Terminal - SET) is served by a radio base station (eNode B) via a radio interface Uu, while managed by a mobility management entity (MME) in the core network. The location server platform includes an evolved serving mobile location center (E-SMLC) and a SUPL Location Platform (SLP) but also gateway functions towards applications and different sources of assistance data. One such source of assistance data is a GNSS RTK correction provider.

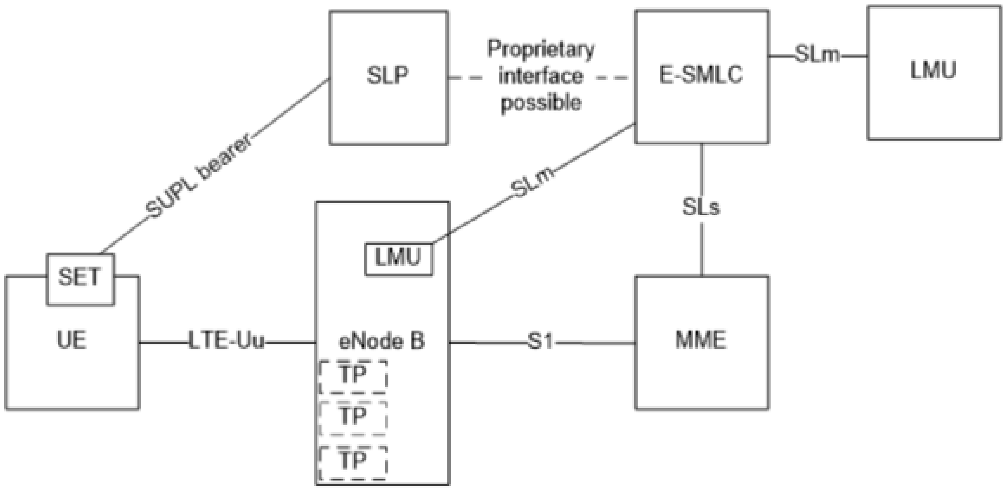


Figure 30. 3GPP LTE positioning architecture

Three different assistance data distribution options are supported:

1. Control plane unicast, with assistance data from a location server (E-SLMC) via the cellular network signaling mechanisms of MME and eNodeB, similar to the ones providing SMS.
2. User plane unicast, with assistance data from a location server (SLP) via secured IP connectivity based on SUPL defined by Open Mobile Alliance [8].
3. Cellular broadcast, with assistance data from the location server (E-SMLC) via base station (eNodeB) system information broadcast

Figure 31 provides a generic picture of 3GPP GNSS RTK assistance data distribution with a GNSS correction data provider signals correction encoded data via some signaling protocol, typically on top of IP to a cellular network location server for scalable distribution to devices.

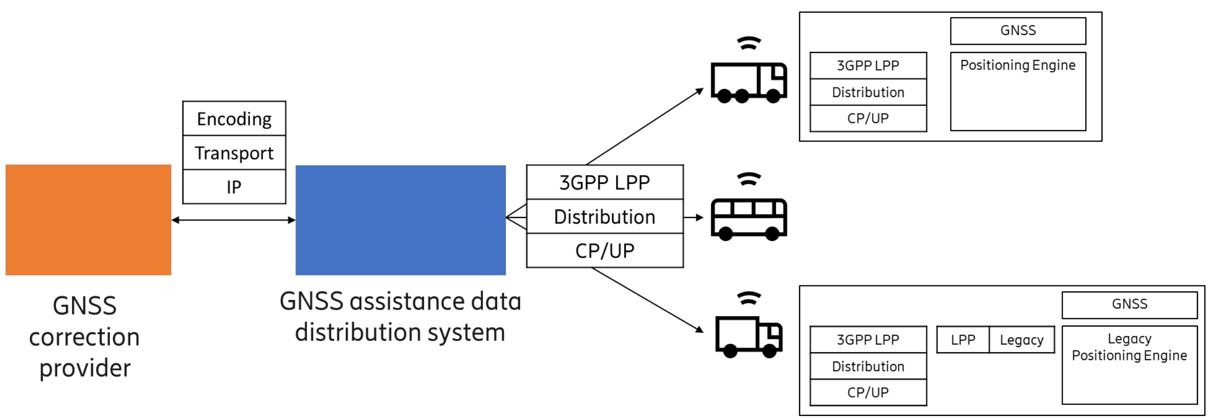


Figure 31. Scalable and interoperable 3GPP GNSS RTK assistance data distribution

Both the unicast signaling protocols (control plane – CP and user plane - UP) can be prioritized in the cellular network for secure and stable distribution. Broadcast distribution is also an example of control plane signaling. The device protocol stack terminates 3GPP LPP. Internally, the device may have a positioning engine with direct support for the LPP information elements, or a legacy positioning engine that needs an internal translation from LPP to some legacy information encoding.

GNSS RTK OSR is traditionally based frequent on bi-directional signaling between device and server, where the device frequently provides information about its position to the server to enable the server to alter the non-physical reference station over time. When the device has moved a certain distance (e.g. 5km) from the current non-physical reference station location, the server determines a new non-physical reference station location for the device, typically the current device location. In 3GPP GNSS RTK OSR, this is not needed in the same way. Instead, the location server obtains GNSS correction data over a grid of non-physical reference stations with an inter-grid point distance (e.g. 5-10 km) as illustrated by Figure 32. The cell radius (some hundreds of meters) is typically much smaller than the grid size, which means that the knowledge of the device serving cell is sufficient granularity of information for selecting an appropriate grid point for a specific device at any point in time.

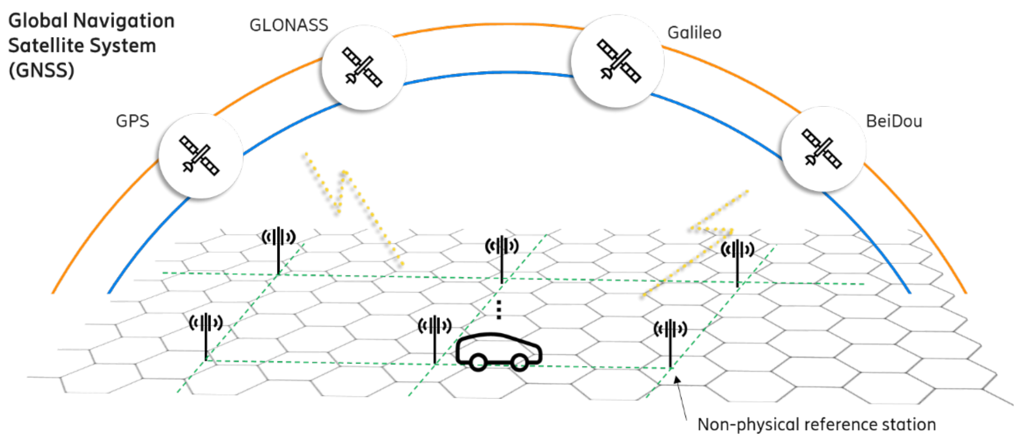


Figure 32. OSR GNSS RTK correction data over a grid of non-physical reference stations overlayed to the cellular network with cells typically with a much smaller radius than the inter-grid point distance of the OSR data.

The serving cell in case of broadcast is the one the device is currently obtaining its system information from, which in idle mode is referred to as the cell the UE camps on. This means that in any of the three distribution options, the UE will obtain GNSS RTK assistance data based on its currently associated cell. This means that even if the broadcast option corresponds to ultimate scalability, it is sufficient to analyze a service provided via unicast to understand the service behavior and service performance from a device and end-to-end perspective.

In more detail, 3GPP LPP defines transactions of messages between a device and a location server. There can be several transactions in parallel, each identified by a transaction ID. GNSS RTK is provided as periodic assistance data with update as described by Figure 33. GNSS RTK session in LPP is initiated by a RequestAssistanceData message (1) from a device, indicating what types of assistance data that is requested, but also additional information such as the ID of the serving cell. The location server confirms the request (2), ends the first transaction and starts a new transaction with periodic assistance data (3, 4) that continues regularly (e.g. every 1s). When the device becomes associated to a new cell, the device starts a new transaction to inform about the cell change (1), which is acknowledged by the server (2). In case the change of cell has impacted which grid point the device is associated to, then the network will alter the periodic data to instead come from a new grid point. The service can be aborted by either the device (5) or the location server (6) and the session ends (7).

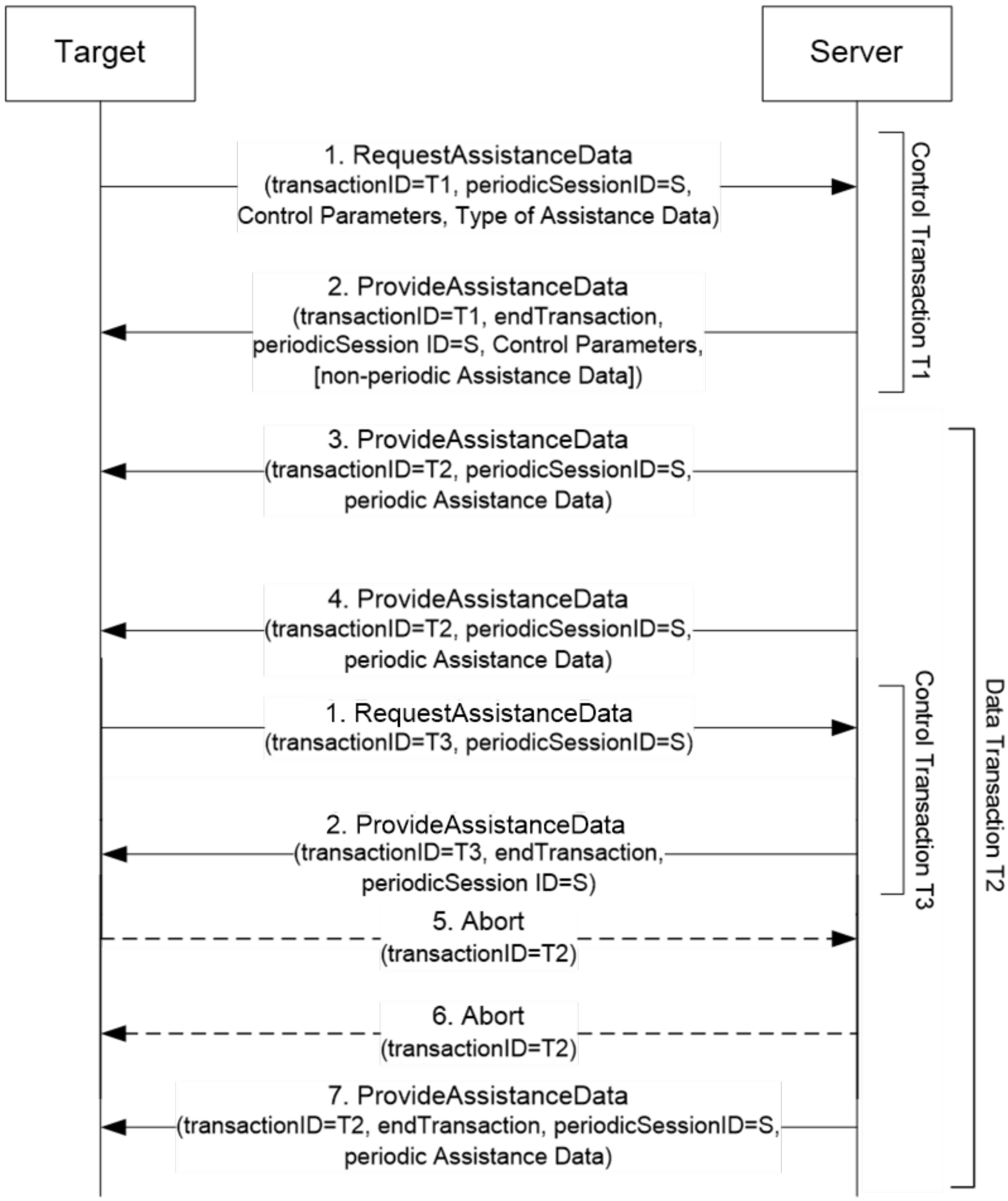


Figure 33. Periodic assistance data transactions via 3GPP LPP.

In case of user plane unicast, the LPP session is handled on top of SUPL signaling, illustrated by Figure 34. SUPL 2.0 or newer is required for 4G/LTE/EPC and 5G/NR/5GC support. The session is initiated by the device (SET) with a SUPL START message to the location server (SLP), which is confirmed by the server with a SUPL RESPONSE message. The session is initiated and the LPP transactions described by Figure 33 are exchanged within the SUPL POS block.

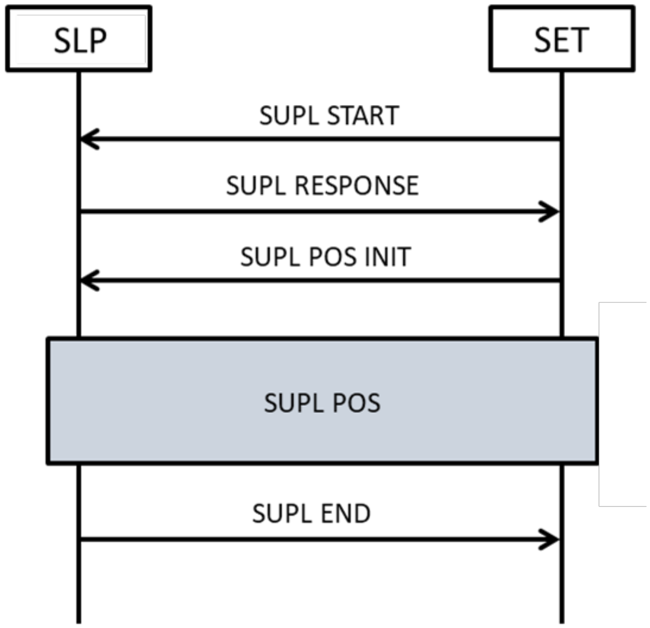


Figure 34. User plane unicast session via SUPL signaling [8].

6.3.2 GNSS Reference data distribution in NPAD

The NPAD project has considered the user plane unicast distribution option based on SUPL, which will without loss of generality enable an analysis of the end-to-end performance of 3GPP GNSS RTK. The architecture is described by Figure 35. The correction data is provided by Lantmäteriet using NTRIP signaling of RTCM v3.x messages with OSR data over a grid of non-physical reference stations as illustrated by Figure 32, and described in more detail in Section 6.2. The Ericsson location server (ENL NLG SLP) converts and stores the data, and upon request established SUPL sessions with devices. The data is provided as 3GPP LPP release 15 OSR to the device.

Two different device architectures are considered. Both are based on a SUPL/LPP terminal protocol stack by Ericsson. In one device type, the LPP assistance data is used directly with the RTKLIB positioning engine, while in the other device type, the LPP assistance data is first converted back to RTCM in order to use a legacy positioning engine. Further details are provided in Section 6.4.

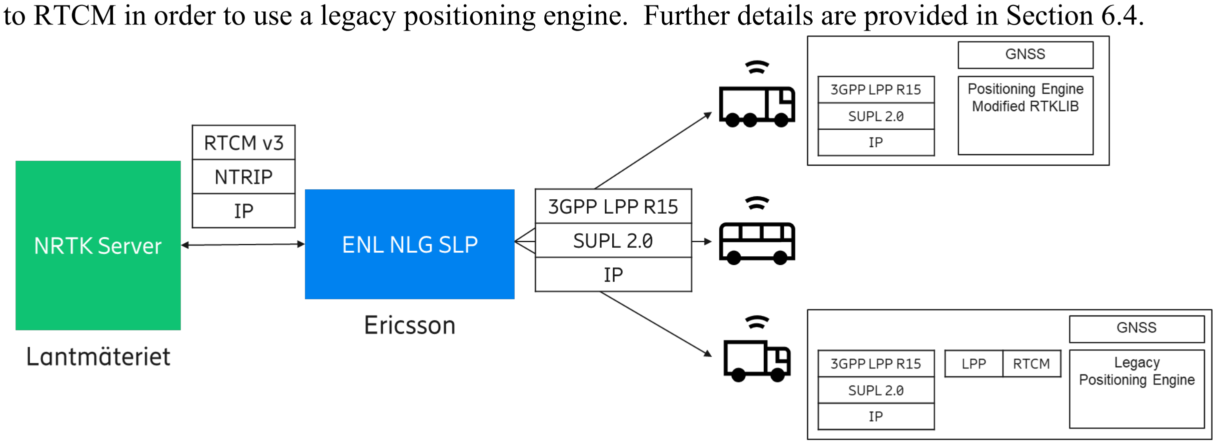


Figure 35. GNSS RTK correction data distributed via 3GPP LPP and SUPL to capable devices.

6.4 RTK GNSS Client System Design

Within NPAD, the scalable distribution of GNSS corrections for precision positioning over mass market channels need to be demonstrated. To achieve this, the corrections distribution, and its suitability for autonomous driving, precise positioning clients integrated into autonomous vehicles are required.

This section describes the client-side architecture as implemented as part of the project. It covers the data sent and message sequencing between functional components and the physical overview of the system. Detailed internal software design is not covered in this section.

6.4.1 System Overview

This section briefly describes the overall NPAD system architecture in a simplified format for the purpose of placing the client within a larger context.

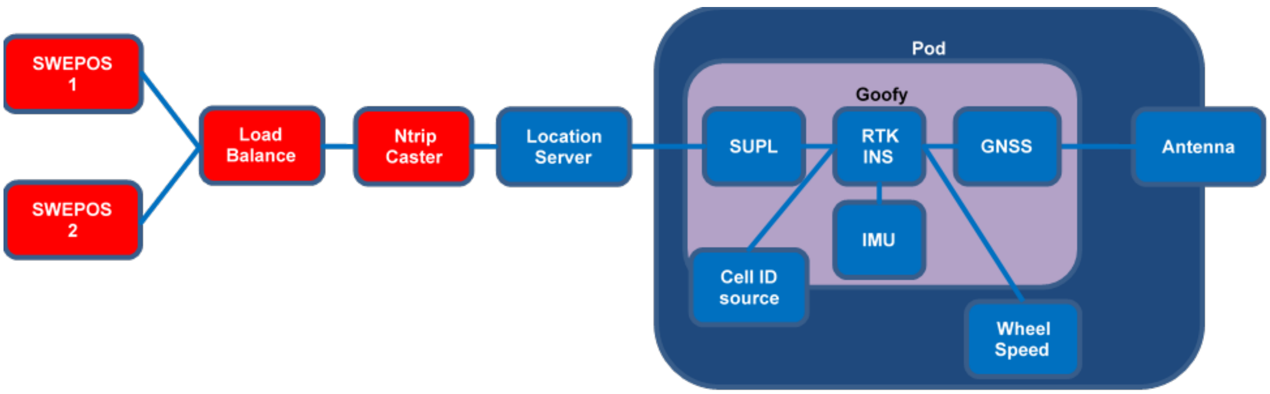


Figure 36 Simplified Functional Architecture

The simplified data flow of the NPAD Project is as follows:

- The SWEPOS VRS NTRIP casters provide observation streams preconfigured in line with the defined grid layout from the Trimble VRS correction service, through a load balancer and on to the dedicated NPAD NTRIP caster.
- The location server receives these observation streams from the NPAD NTRIP casters for further distribution.
- The SUPL client sends a cell ID to the location server as part of a SUPL session and the location server responds by providing the most appropriate observation stream back to the client.

Within the client the RTK INS fuses Wheel speed, IMU, local GNSS measurements and the observation data stream to provide positioning to the Autonomous platform (POD).

6.4.2 Physical Description

This section describes the installation of the positioning solution in the Einride Pod, covering physical and electrical aspects.

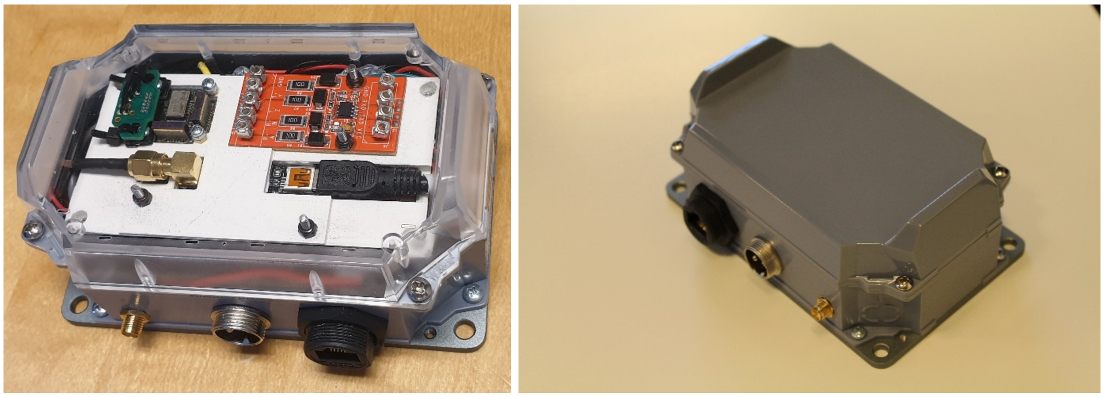


Figure 37 Goofy Platform

Figure 37 shows an image of the "Goofy" platform. The Goofy platform houses a GNSS receiver, an IMU, and a processing platform for the integrated positioning software. The platform communicates over an RJ45 ethernet connection. It connects to an active GNSS antenna (5V) through an SMA connector and is powered with a 5V/2A supply.

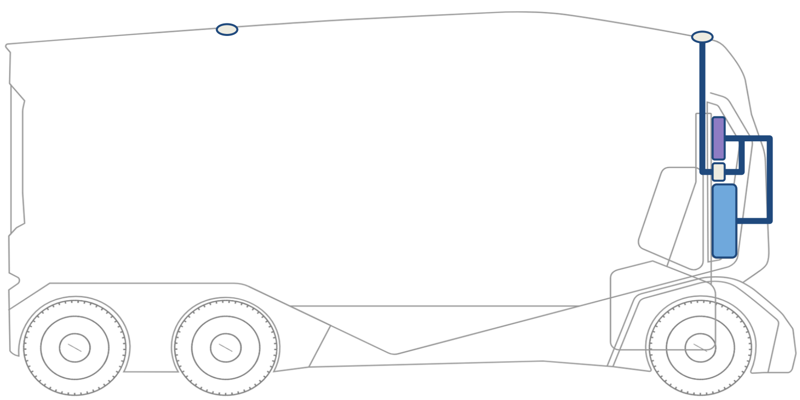


Figure 38 - Installation in the Pod

Figure 38 above describes the installation of the antenna and Goofy in the Pod. The antenna is located laterally central on the roof of the Pod, at the front of the vehicle. This is above the equipment bay of the pod, which houses the Goofy platform, modem and other electronics required for sensing, perception and control of the Pod.

6.4.3 Client Software

This section describes the component responsibilities and data flow between the Goofy unit and the other components in the client system.

6.4.3.1 Functional Overview

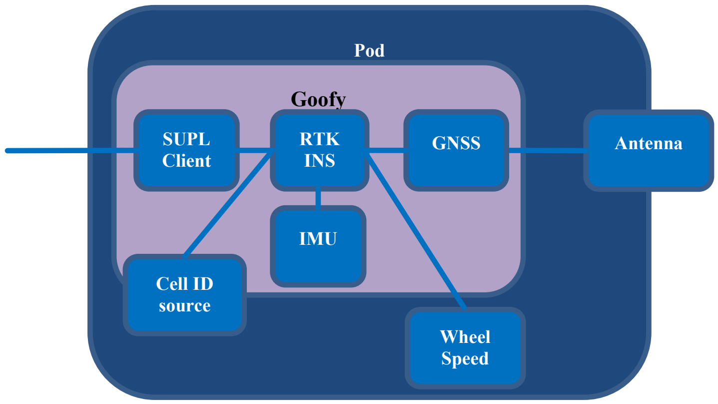


Figure 39 - Client functional overview

SUPL Client

This component is responsible for converting the ASN.1 encoded data sent to and received from the location server to typed separated variables available over functional APIs.

IMU

This component provides body frame rotational rates and accelerations to the RTK INS for fusing.

GNSS

This is responsible for the reception of RF data from the antenna, down conversion and acquisition and tracking of the GNSS measurements. The GNSS unit subsequently provides GNSS raw measurements to the RTK INS component.

Wheel Speed

This module is responsible for providing odometry data from the vehicle drive system or wheels themselves.

RTK INS

This component combines wheel speed, inertial measurements, and GNSS measurements from the network and the local receiver to provide position to the hosting system.

Cell ID Source

This component provides the cell ID to the SUPL Client. In a production system this would be facilitated by the modem itself, and the location server would require associations between the cell IDs in use and the VRS grid points that provide the observation stream. For the purposes of the project, this function has been separated to allow simulated serving cell ID changes between known configured cell IDs. The change in serving cell can therefore be caused by the following methods:

- **Time** – the client software selects an initial cell ID (either hardcoded or based on position/cell ID), then after a certain period, the client software changes to another preselected cell ID.

- **Position(geofence)** – Each cell ID has a region defined around it, and upon entering/exiting that region the cell ID changes.
- **Cell ID from the modem** – this would require an integration to the modem API to receive the full cell ID and a mapping between the cell IDs in use by the modem to the location server. This method would be most representative of a production system.

Antenna

The antenna in the system is automotive grade, multiple frequency patch antenna.

6.4.3.2 Internal APIs

Data transferred between the Waysure positioning unit and the Pod system is sent over LCM, except for the external connectivity (to the Location server), which is provided over TCP/IP. The internal network in the Pod provide internet connectivity through cellular routers.

Position data – output from Goofy to Pod

Name	Type	Units	Notes
Timestamp	Uint64	Nanoseconds	TAI
Latitude degrees	Double	Degrees	WGS84 - Reference dependent on correction service
Longitude degrees	Double	Degrees	WGS84 - Reference dependent on correction service
Altitude meters	Double	Degrees	WGS84 - Reference dependent on correction service
Heading degrees	Double	Degrees	
RTK Status	RTK Status enum	N/A	See RTK Status enum
Number of used satellites	Uint32	N/A	
PDOP	Double	N/A	Position dilution of precision
Is leap seconds valid	Boolean	N/A	Relates to leap seconds parameter
Leap seconds	Uint32	Nanoseconds	UTC = TAI – leap seconds
Device ID	String	N/A	Unique ID of the device, mac if Wi-Fi connected
Horizontal std meters	Double	Meters	Horizontal standard deviation of the position estimate

Name	Type	Units	Notes
Vertical std meters	Double	Meters	Vertical standard deviation of the position estimate
Is Position Trustworthy	Boolean	N/A	True if position and uncertainties have integrity
Error ID	Error ID enum	N/A	See Error ID enum
Error description	String	N/A	
Heading std degrees	double	Degrees	Standard deviation of the heading estimate

Table 8 - Position Data

Wheel speed – input from Pod to Goofy

Name	Type	Units	Notes
Wheel Speed	Uint32	Km/h	Used only for stationary detection

Table 9 - Wheel Speed

RTK Status enum

Name	Value	Notes
RTK Status Invalid	0	Default value
RTK Status uninitialized	1	Data accumulation prior to initialization
RTK Status Initializing	2	Initializing
RTK Status Too Few Satellites	3	Unable to position due to available satellite measurements
RTK Status Float	4	Solution with Float Ambiguities
RTK Status Fixed	5	Solution with Fixed Ambiguities

Table 10 - RTK Status

Error ID enum

Name	Value	Notes
Error ID Invalid	0	Default value
Error ID No Error	1	No Errors detected
Error ID Other	2	System errors with no predefined ID
Error ID No Meas	3	Timeout from network or local receiver

Table 11 - Error ID

SUPL messages

The specification for the sequencing of the location server to SUPL stack communication can be found in the SUPL specification [8].

6.4.4 Client message sequences

SUPL message sequencing, where GMPC is the location server and SET is the client.

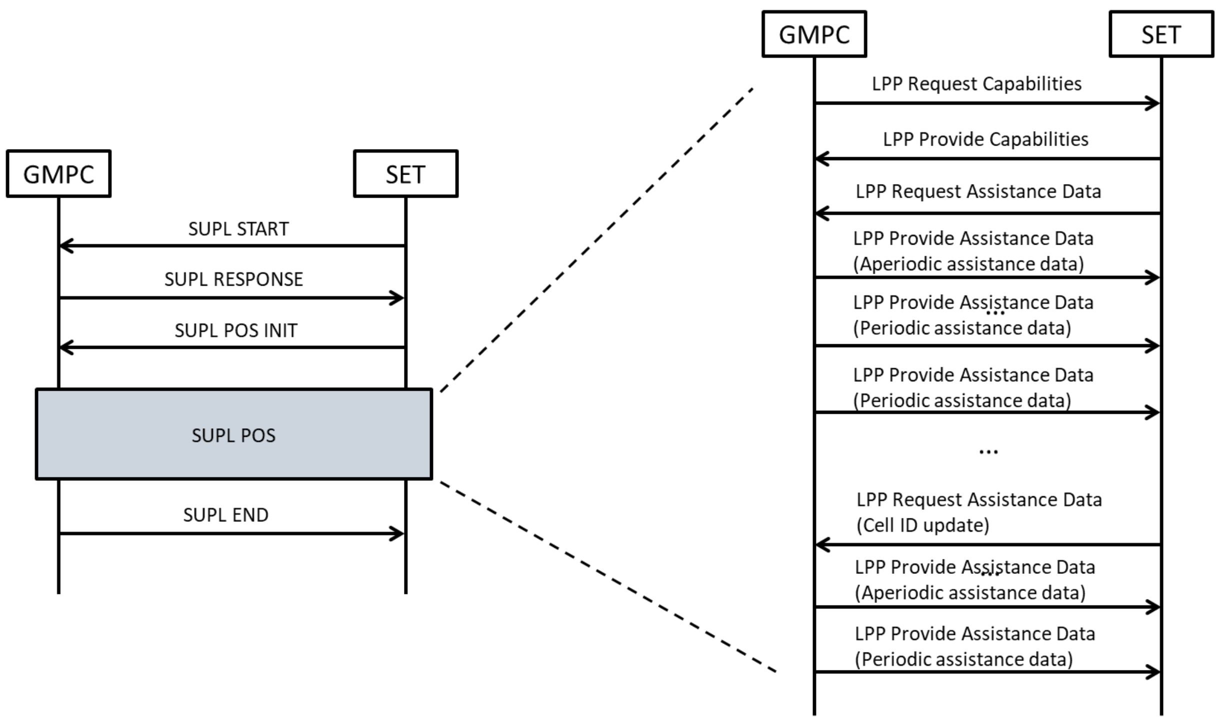


Figure 40 - SUPL Sequence

6.5 Integration and Test

This section describes the integration and tests performed within the NPAD project. Please note that we had to limit the amount of test scenarios (as described in section 6.1.5) we were able to perform due to limitations of time and resources required to cover all scenarios. The scenarios were restricted to the Rural Road (see section 6.1.5.2) and tests performed at a Transport Hub was not performed at the AstaZero City Area, but emulated at the AstaZero Garage Plan. Additionally, we also performed ad hoc tests along highway 40 between Borås and Gothenburg.

6.5.1 Integration and test of Navigation Solution in Einride Platform

6.5.1.1 Hardware setups

Einride Pod

The Einride Pod has been used to test the position measurements from the Goofy receiver. The Goofy box was placed inside the electronics bay at the front of the Pod. The GNSS antenna was placed on top of the Pod, at different locations depending on the test performed. The antenna cable was fed straight to the Goofy. An ethernet cable was connected from the Goofy to the main ethernet switch available in the Pod (providing network connectivity and internet access). Power was connected to the Goofy with a standard USB 2A charger connected to a 230V power outlet available in the Pod.

The measurements from the Goofy receiver could then be used in the localization stack on-board the Pod instead or in combination with the other standard RTK-GNSS receiver measurements nominally used for localization of the Pod.

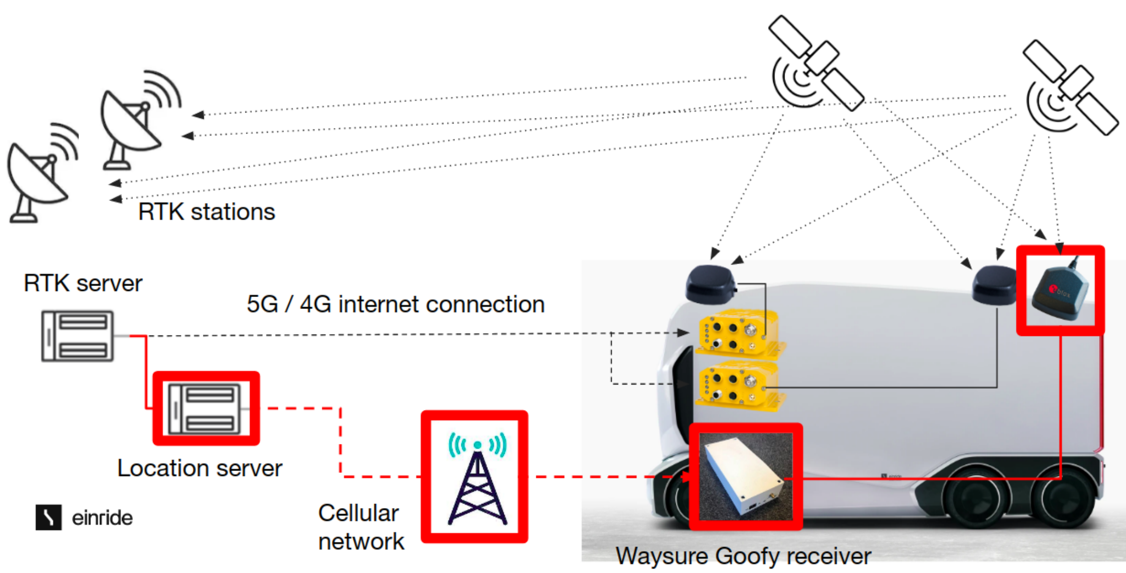


Figure 41 Test setup with the Goofy box integrated on the Einride Pod

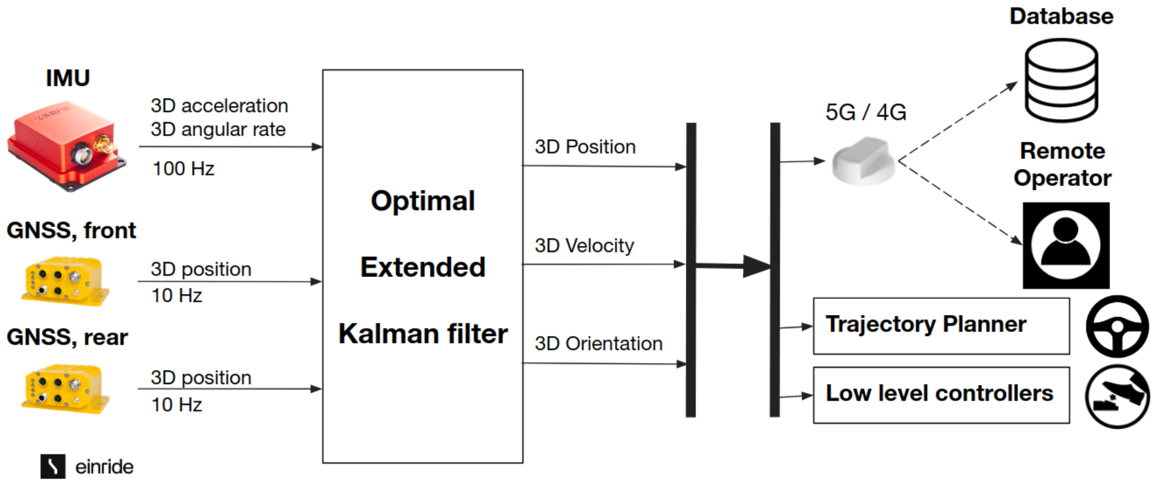


Figure 42 The Einride high accuracy GNSS-based localization system

Einride test vehicle

As an alternative to the Einride Pod, another test vehicle, equipped with the same localization stack as the Pod, has been used during the project to test the NPAD technology on public roads and at higher speeds.

The Einride test vehicle has been used in a late phase of the project, in addition to the Pod, in order to accommodate a SUPL Client Stack box as described in section 6.5.3. Instead of being connected directly to the internet and to the SWEPOS correction data, the RTK-GNSS receivers inside the test vehicle were connected to the SUPL Client Stack.

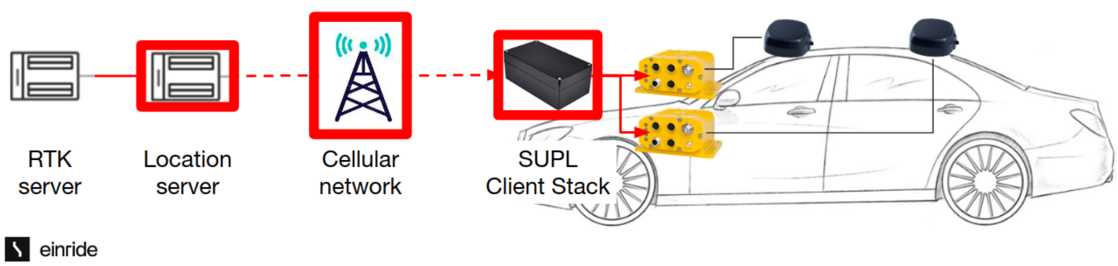


Figure 43 Test setup with the SUPL Client Stack box integrated on the Einride test vehicle

6.5.1.2 Test Environments

AstaZero

Most of the tests were conducted at the AstaZero testing facility, in the area of the garage. See Figure 44 below for an overview of where the tests took place. The area provides good sky visibility, meaning GNSS conditions are not challenging. The point marked "VRS 1" is the location of the Virtual Reference Station providing RTK correction data to the Ericsson Location Server (ELS), this point is known at Swepos as "VRS1AstZ". See Figure 45 below showing both VRS 1 and VRS 2, where the VRS 2 was used as the secondary reference station in the handover driving test.

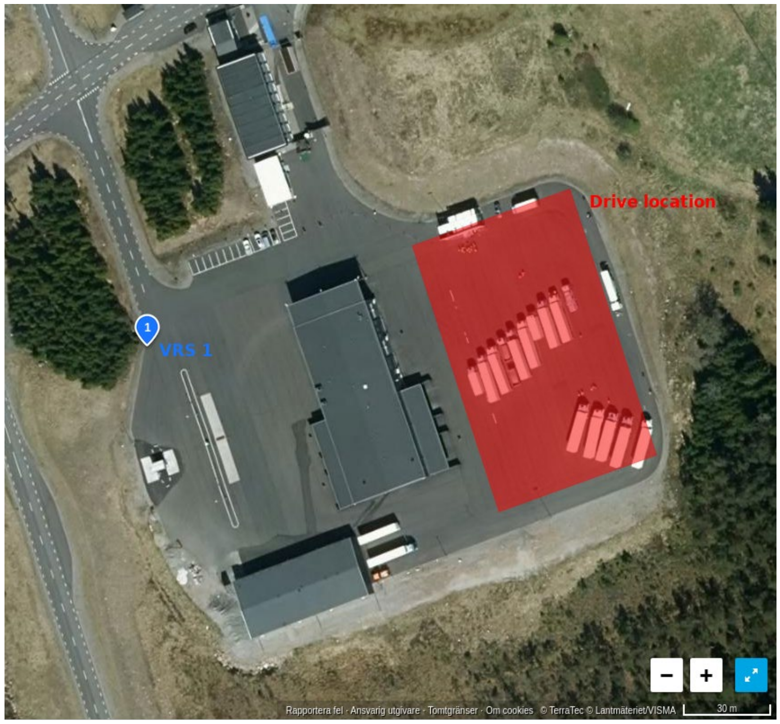


Figure 44 Location of the tests. Image from Eniro.se.

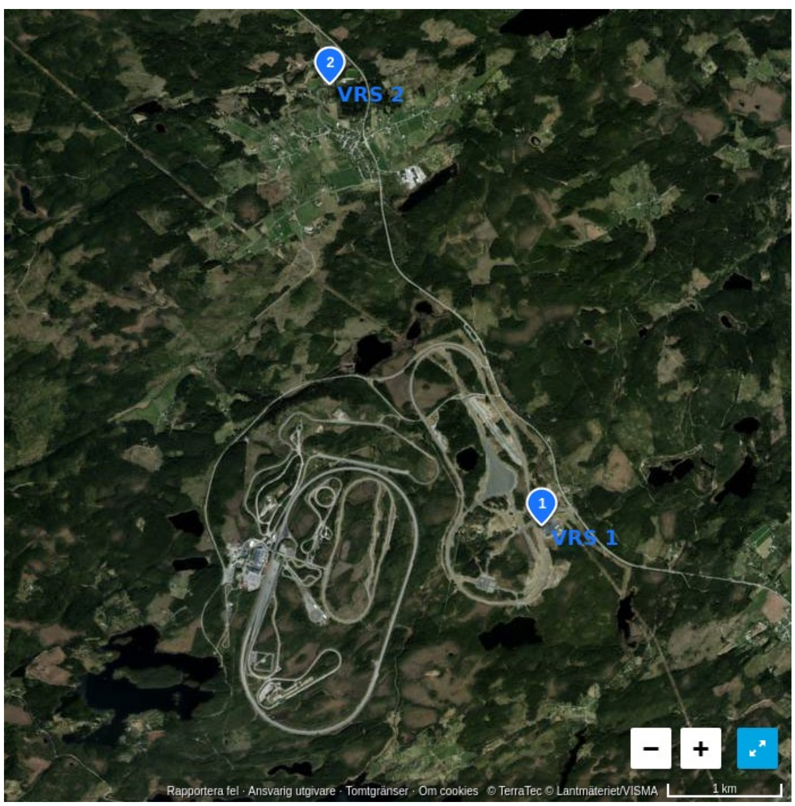


Figure 45 Relation of the two virtual reference stations available. Image from Eniro.se.

RV40 between Bollebygd and Göteborg

Test have been performed between Bollebygd and Göteborg to test switch between virtual reference stations in real drive conditions (velocities up to ~100km/h), and to evaluate the impact on the localization system.

During the test, 3 VRS have been used:

- VRS #8 at start (AstaZero, default)
- VRS #19
- VRS #20

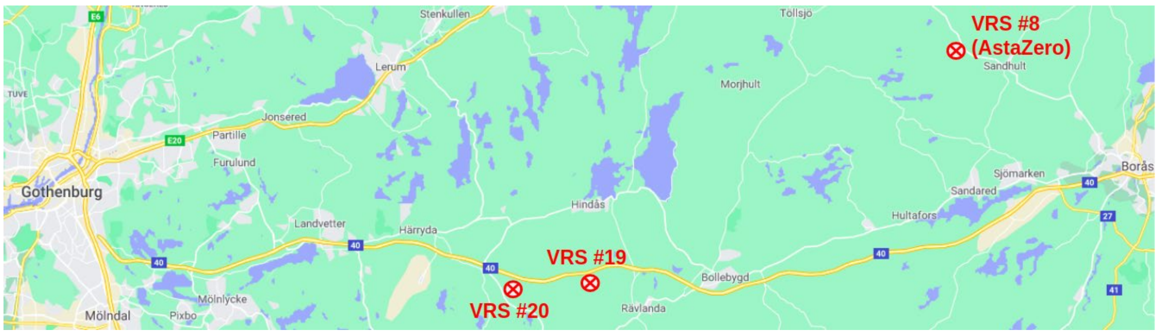


Figure 46 Virtual Reference Stations between Bollebygd and Göteborg (image Google)

The road provides significantly more challenging conditions for the localization system: sky visibility is not always optimal, several bridges completely block the GNSS signals and cause outages, and high voltage lines generate interferences.

6.5.1.3 RTK Correction data

Swepos provided each VRS correction stream as an NTRIP data stream to the ELS. The correction data was subsequently taken in SUPL/LPP format from the ELS to the Einride Pod "over the top", meaning through an internet TCP/IP connection to the ELS. For the ELS to know which VRS stream was appropriate an approximate location for the pod was required. Rather than us the position of the Pod, a cell tower unique ID was sent which could be related to a position and VRS stream in the ELS. The cell information ID in the correction data request was manually configured (i.e. not taken from an LTE modem or similar). Internet connection was provided by an onboard 4G modem in the Pod, through Telia.

6.5.1.4 Test cases

- **Static test with Goofy box:** Pod on the garage plane with corrections from VRS 1, no motion.
- **Motion test with Goofy box:** Pod on the garage plane with corrections from VRS 1. Driving initially in an arc to the west, then turning and heading south before ending with a turn to north-east. Measurements from the Goofy box are logged for offline analysis, but not used on-board.
- **Simulated reference change:** The same input data as in "Motion test **with Goofy box**" but replayed at a later time, together with simultaneous corrections from VRS 2. In the replayed scenario, a reference station switch from VRS 1 to VRS 2 is carried out upon reaching a certain coordinate on the driving path. Note that RTK ambiguities are not levelled between VRS 1 and VRS 2 but are recalculated in the RTK software solution.
- **Closed-Loop Autonomous Drive test with Goofy box**: Pod on the garage plane with corrections from VRS 1. The Goofy measurements are used as input to the localization

system, and the output from the localization service is used in the control loop to autonomously drive the vehicle along a pre-defined path. The Goofy measurements have been used either in complement to the nominal RTK-GNSS measurements (front and rear measurements) or in replacement to the rear GNSS. The path includes portions in both forward and reverse directions.

- **Localization test with the SUPL Client stack box:** The Einride test vehicle drives on RV40 between Bollebygd and Göteborg. RTK corrections are provided to the nominal GNSS receivers, and VRS stations are switched automatically at several occasions. The localization service runs in real time based on GNSS measurements.

Test results from the above test cases are provided in the following section.

6.5.1.5 Test results

Static Test

Date: 2020-02-03

Present: Waysure and Einride

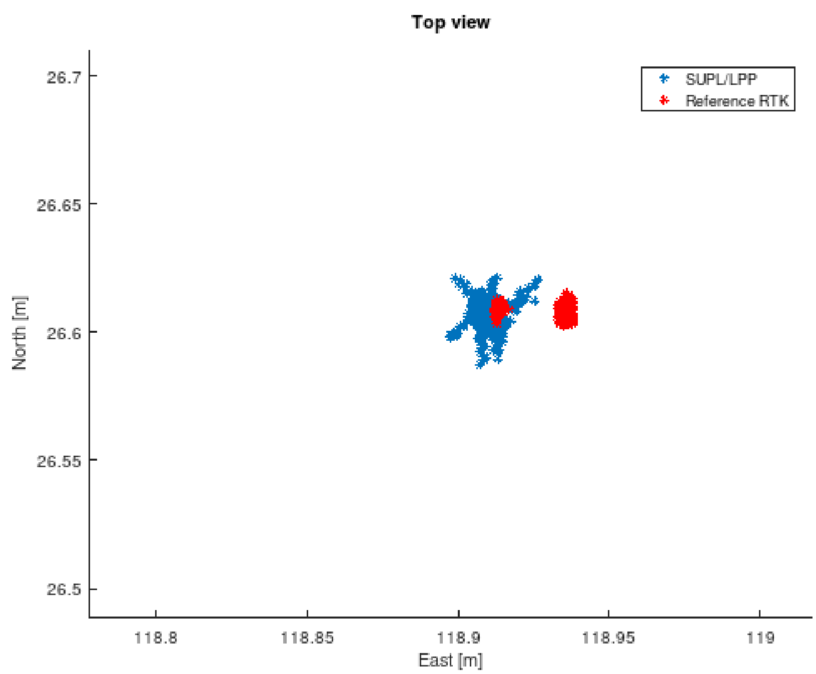


Figure 47 Static positioning results comparing 3GPP compliant and reference solutions

Figure 47 shows that the 3GPP compliant solution to have similar absolute positioning performance when compared to the RTK reference solution. The reference solution shows an adjustment in its estimate of around 2 cm. The 3Gpp solution show higher noise around its position estimate, however both solutions agree, and the adjustment and noise are well within the expected performance of the system. Figure 48 shows that the 3D error is slightly larger which is to be expected due to the inherent lower accuracy in the vertical direction from GNSS positioning systems. These errors are also well within the expected performance requirements.

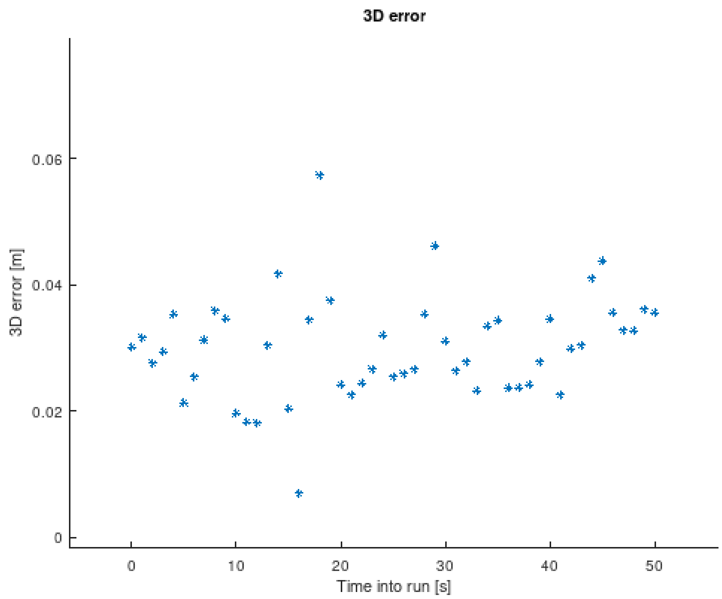


Figure 48 3D position error comparing 3GPP compliant solution and reference solution.

Motion test

Date: 2020-02-03

Present: Waysure and Einride

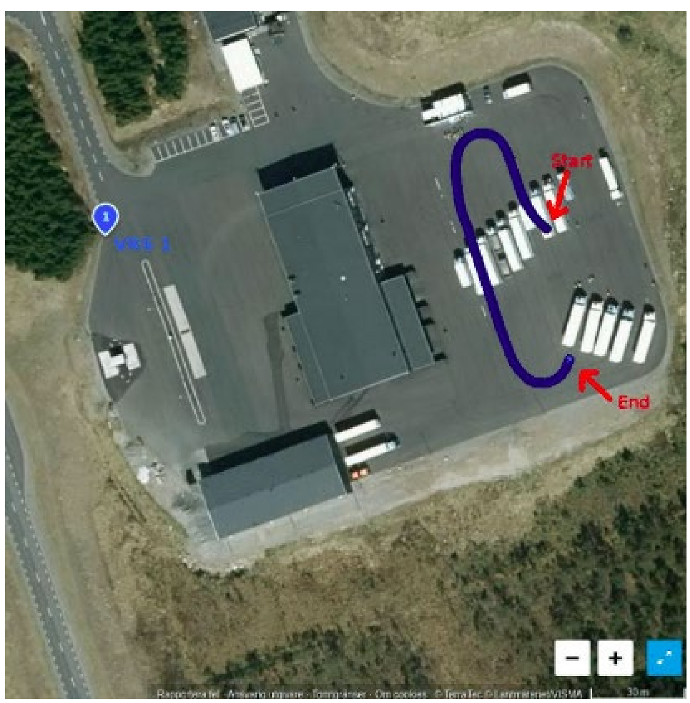


Figure 49 Driven path during the motion test. Image from Eniro.se.

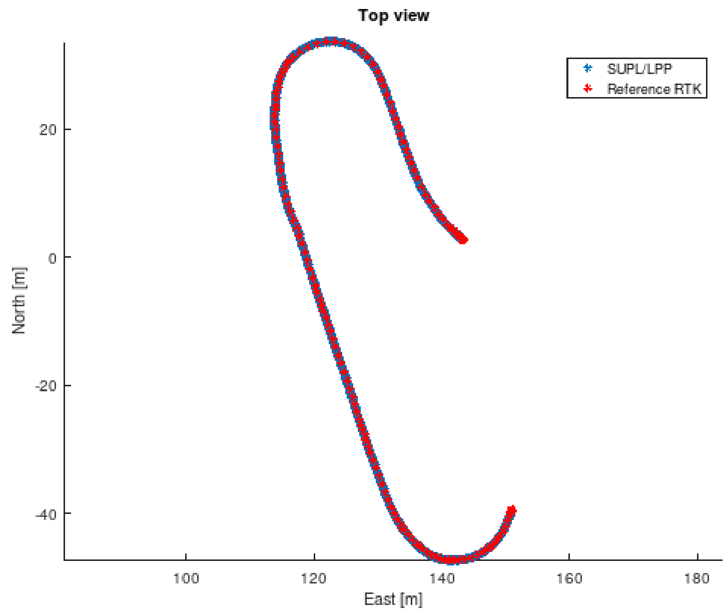


Figure 50 Comparison of NPAD 3GPP compliant solution and reference positioning tracks.

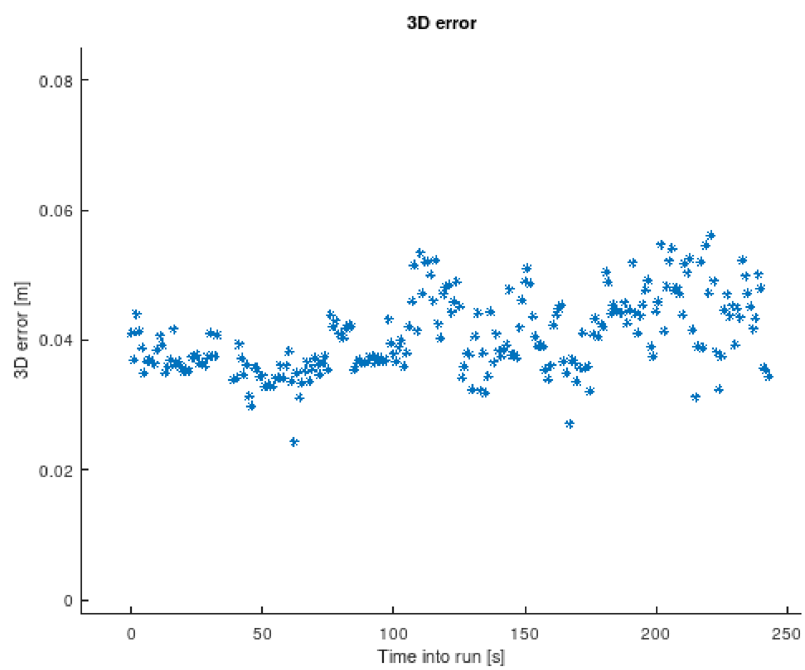


Figure 51 Time series showing position error between 3GPP compliant and reference solutions.

Figure 50 and *Figure 51* above show that even under motion the 3GPP compliant solution meets the expected performance of the system.

Simulated reference change

The simulation is based on the same data as presented in the previous section.

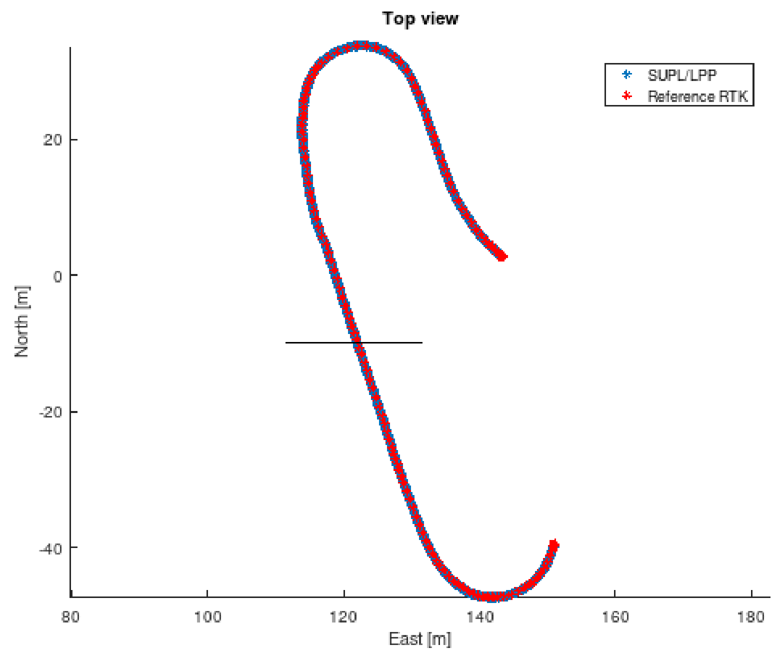


Figure 52 Change from VRS 1 to VRS 2 is simulated at the black horizontal line.

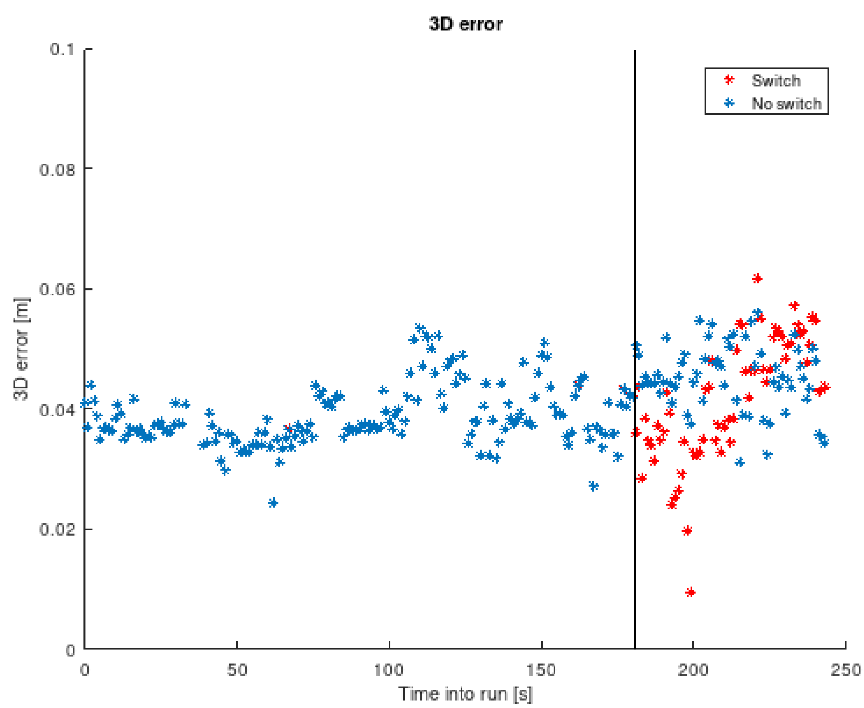


Figure 53 Comparison of errors after switching VRS at the black line, the run with simulated switch (red) overlaid on the run without switch (blue).

Figure 52 and Figure 43 above show that the performance is unaffected by a change of VRS. This shows that the mobility goal of the NPAD project can be met, as VRS handover can occur without impacting the availability or the accuracy of the resulting position estimate.

Closed-Loop Autonomous Drive test with Goofy box

Date: 2020-05-05

Present: Einride

Several tests have been performed with the Goofy Box, where outputs of the box were used in the Pod control loop to autonomously drive the Pod on the test area. The antenna used for the Goofy receiver was located very close to the Rear antenna, so that the Rear GNSS measurements and the Goofy measurements were expected to be close to each other.

Here is an example that shows the GNSS measurements on one test example, when the Goofy measurements were used in complement to the nominal Rear and Front RTK-GNSS measurements.

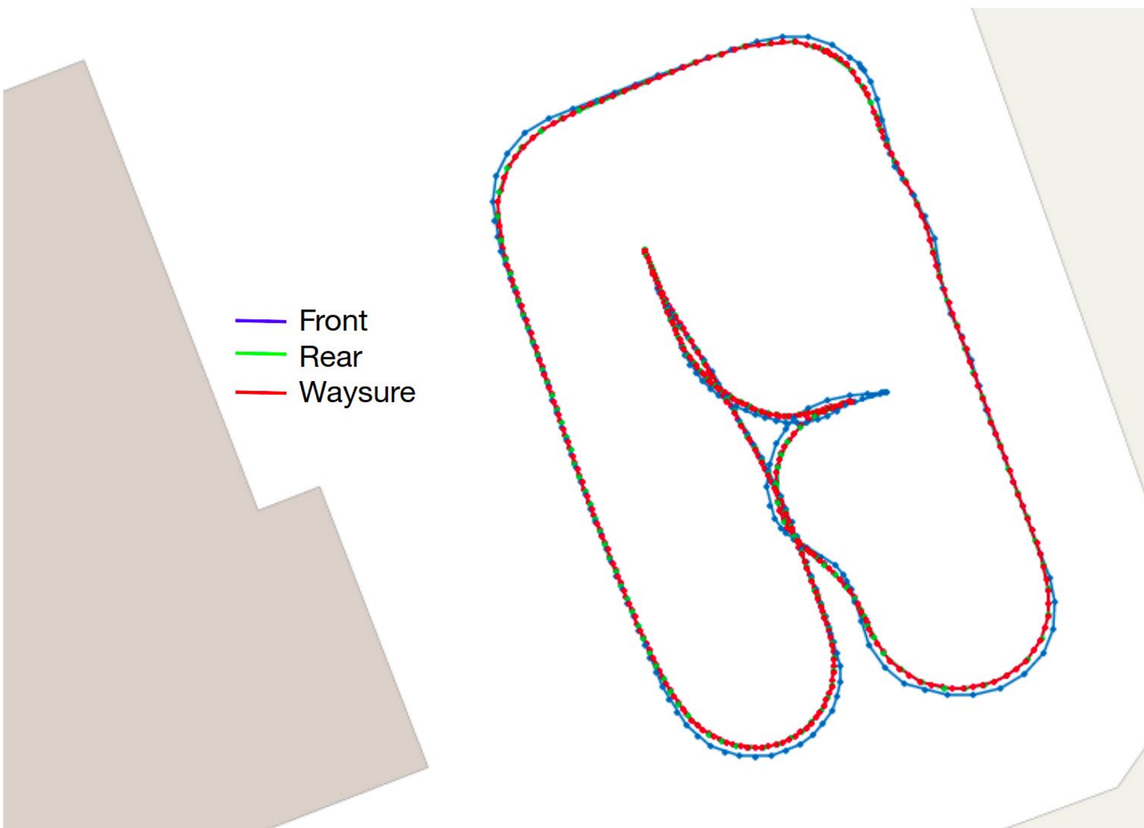


Figure 54 Einride Pod's autonomous motion on AstaZero garage plane with Goofy measurements used in the localization and in the control loop (map source: OpenStreetMap)

These test results show that it was possible to follow the desired path at the desired speed and with the desired accuracy.

Localization test with the SUPL Client stack box

Date: 2020-12-09

Present: Einride

The Einride test vehicle started to drive from Bollebygd on RV40 and continuously to Göteborg. The SUPL Client Stack box provided the correction values to the nominal RTK-GNSS receivers in the test vehicle, whose measurements in turn were used in the localization filter on-board as done in the Pod.

All time stamps in this section refer to the start of the test at **T0 = Wednesday, 09-Dec-20 15:28:52.1095 UTC**

The following figure shows the GNSS solution type evolution for both GNSS receivers.

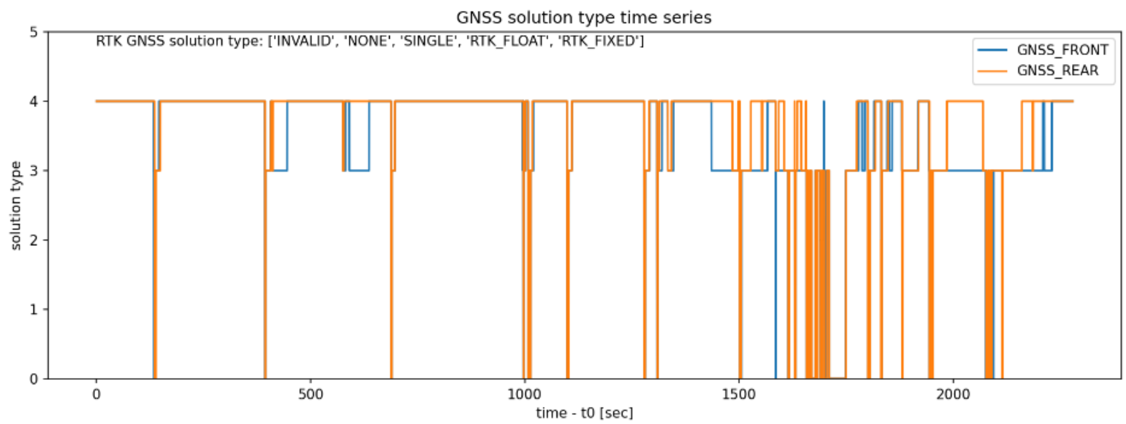


Figure 55 GNSS Solution Type during the Localization test with the SUPL client stack box

The test vehicle drove several times under bridges, which explains several complete outages. Some perturbations were also noticed in the vicinity of high voltage lines. From t ~1500s, the test vehicle entered Göteborg urban area, where outages become more frequent. Test analysis focuses on the period prior to t = 1500s.

Since it is difficult to get a valid evaluation of the true position during this test, two main indicators have been used to evaluate the performance of the localization system:

Distance between the GNSS antennas

The indicator is obtained by computing the distance between the two measured GNSS positions, whenever the measurements were fully synchronized and had both an RTK Fixed status. The distance between the antenna gives a good performance indicator for all error contributors not common to both GNSS receivers.

The evaluation on the distance between antennas is shown below.

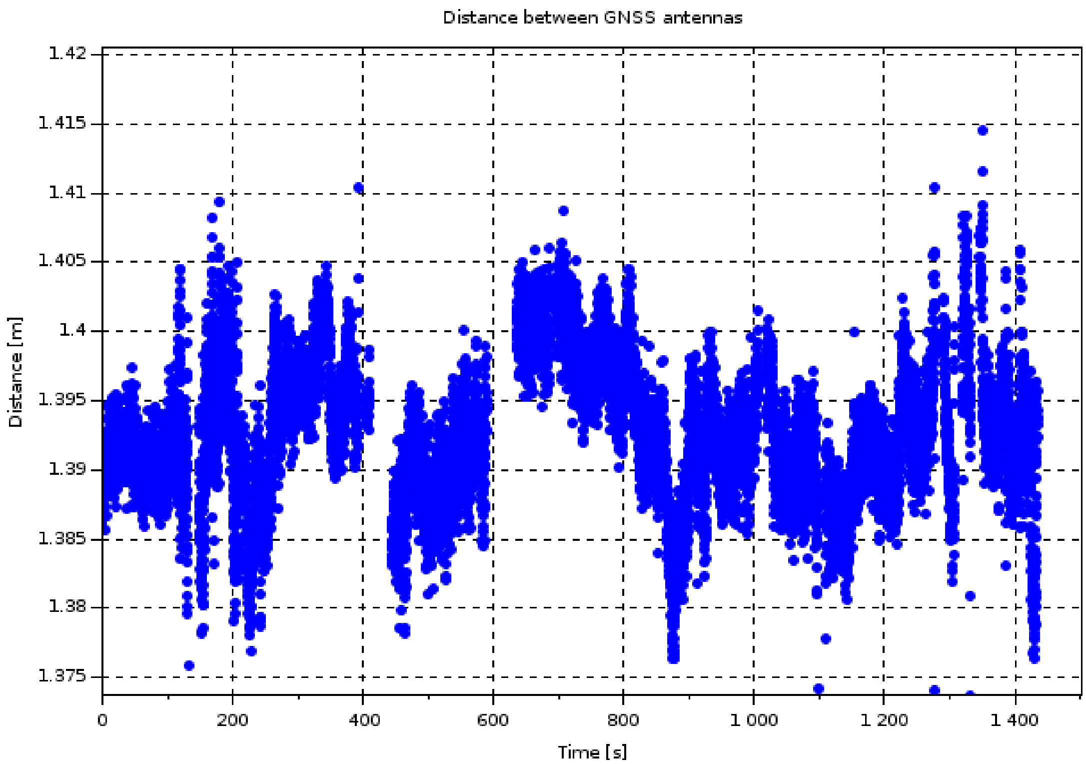


Figure 56 Measured distance between GNSS antennas during the Localization test with the SUPL client stack box (excl. positions close to bridges)

Except in the close vicinity of bridges (remarkable by high PDOP / HDOP values) the distance is always between 1.375m and 1.41m (+/-1.75cm from the mean value around 1.3925m).

Localization filter innovation

In the on-board localization Kalman Filter, the "innovation" corresponds to the distance between the "propagated position" (i.e. position propagated since the previous measurement time using IMU measurements) and new GNSS measurements. The innovation is a good performance indicator for all error contributors with low time correlation (e.g. pure white noise).

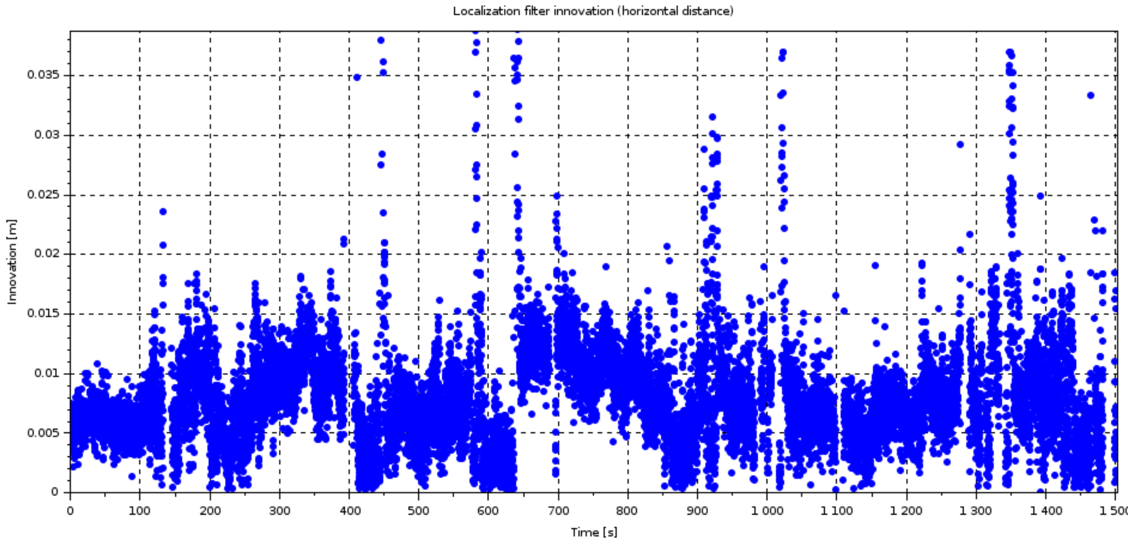


Figure 57 Localization filter innovation (horizontal) during the Localization test with the SUPL client stack box (excl. convergence periods after outages)

Except when the filter needs to re-establish full performance after GNSS outage periods, the horizontal component of the localization filter innovation is always less than 3.5cm (most of the time lower than 1.5cm).

In order to evaluate the impact of VRS switching, the evolutions of the two previous indicators are analyzed in more details. Two switches occur during the test:

- At t = 407.89s the station switches from VRS #8 (AstaZero, default at start-up) to VRS #19

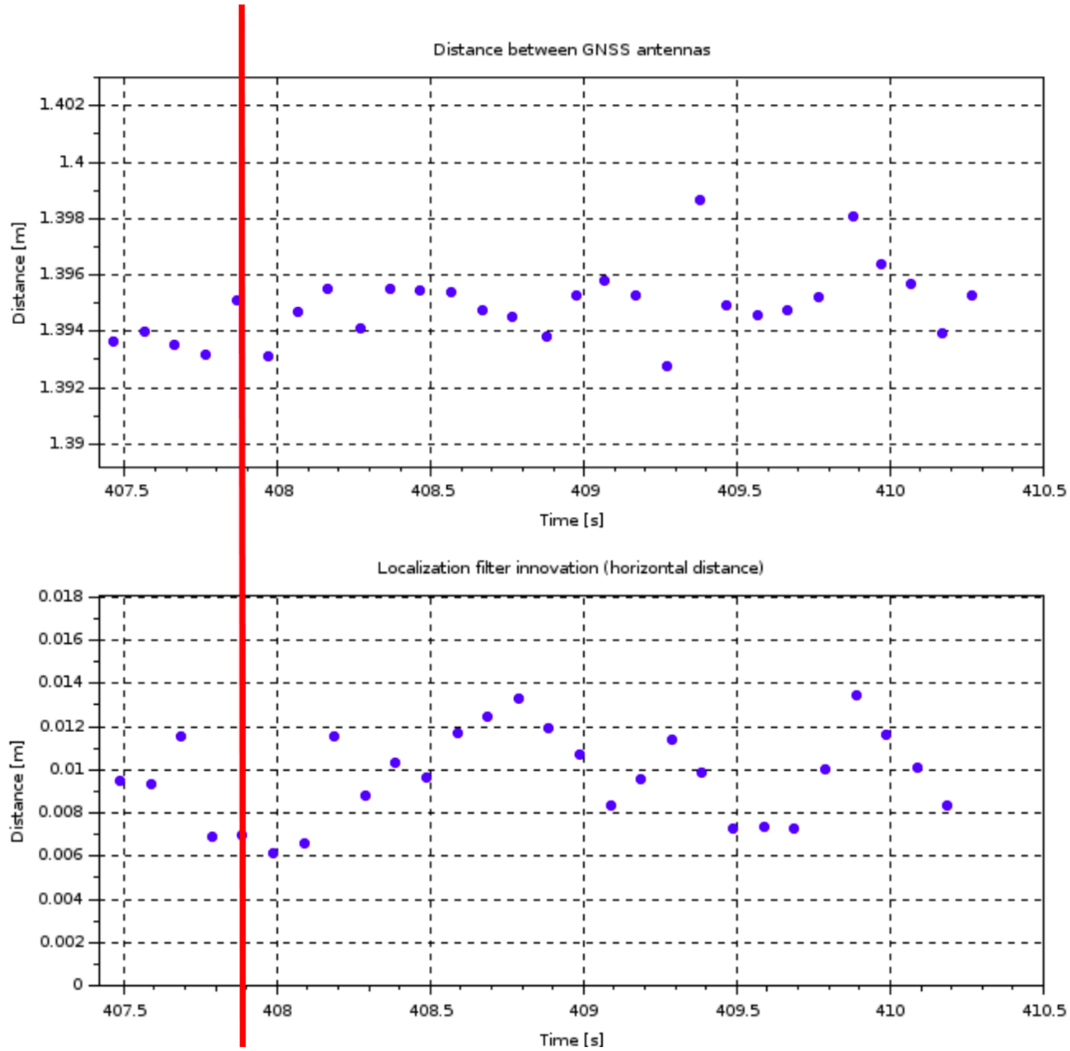


Figure 58 Localization performance indicators during first VRS switch of the Localization test with the SUPL client stack box

- At t = 571.89s the station switches from VRS #19 to VRS #20

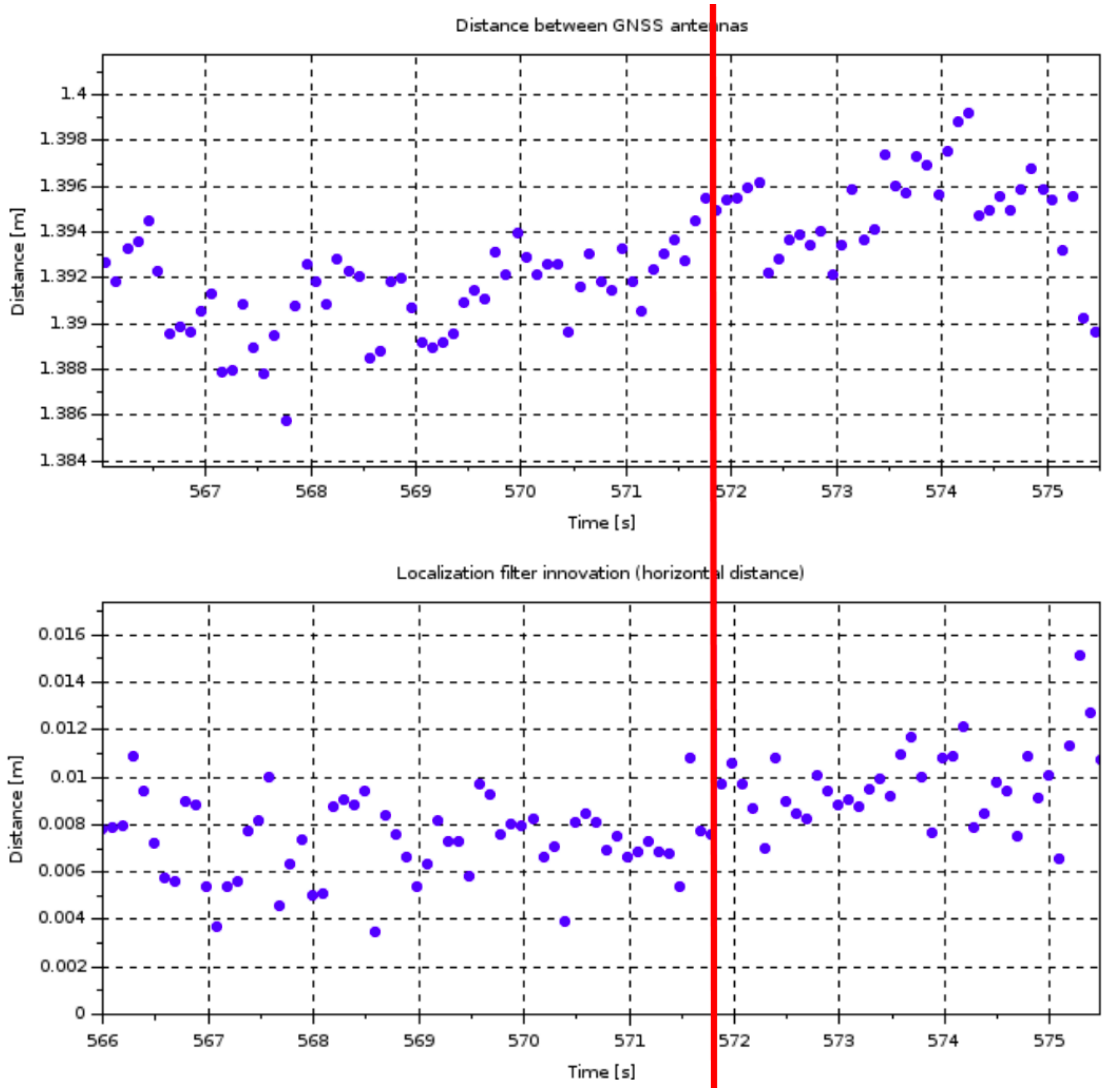


Figure 59 Localization performance indicators during second VRS switch of the Localization test with the SUPL client stack box

From the previous pictures, it can be seen that there is no noticeable jump or change in the performance indicators at the times of the VRS station switches.

Conclusion: All performance indicators show good results, at expected levels (i.e. a few cm). Transitions between VRSs seem to have only little impact on the localization performance.

6.5.2 Integration and test of VRS dynamic behavior and RTK aspects

The purpose of this chapter is report on some interesting activities and investigations regarding integration and testing done during the project. The main part describes the integration of the implemented 3GPP SUPL/LPP distribution of reference data in a kinematic environment, its use with different RTK engines and tests of context changes. This type of tests focused on functionality rather than performance measures.

6.5.2.1 Test Setup

The test setup is depicted in Figure 61. The setup relies on commonly available parts and was initially ad-hoc wired at each testing occasion. In its simplest configuration it consists of an LTE modem with antenna, a laptop computer and an RTK capable GNSS receiver. The modem used is an industrial LTE CAT1 modem from Teltonika using a QUECTEL EC21. The setup usually supports several receivers in zero base line using an antenna power splitter, but receivers can also use a second antenna to support precise heading estimation and is best used with the LEAF platform described later in chapter 6.6.3. Survey grade antennas were usually mounted using magnetic fixtures. Used receivers have varied during testing, but usually consisted of a JAVAD geodetic receiver (Delta, Sigma) with RTK engine connected using Ethernet, and additionally a UBLOX F9P serially connected using USB. The setup also supports the time synchronized connection to one or several IMUs, where an XSense MTi-30 AHRS sometimes was used to collect supporting data.

Testing was done using hired vehicles, at either the Rural Road of the AstaZero test track, Figure 7, or along highway R40 on a stretch between east of Borås and Landvetter Airport. For both test sites the mapping of cells to VRS positions was done and implemented in the Ericsson test location server. Table 12 summarizes the networks used during testing.

Figure 60 typical ad-hoc antenna setup using magnetic fixtures, both for GNSS antennas and LTE antenna. Power was supplied by the vehicle with backup using a LiFePO4 based battery pack.

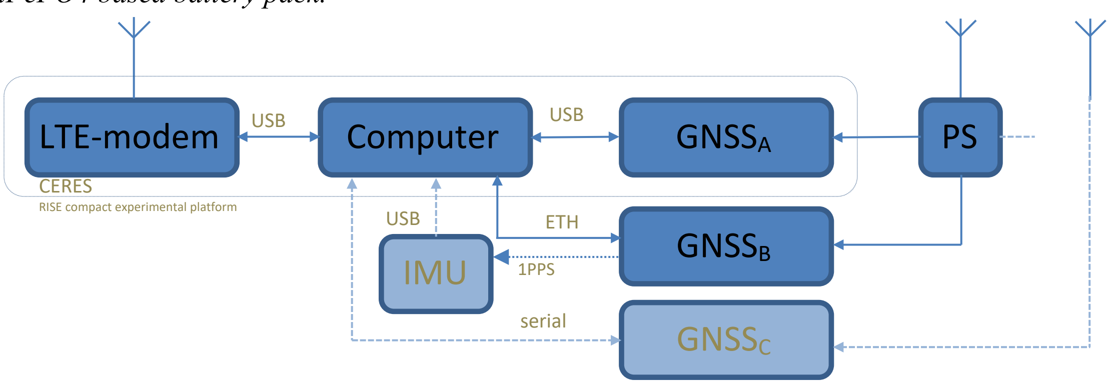


Figure 61 Principle test setup, realized with discrete parts for flexibility. Not shown are power distribution, additional communication paths and other supporting hardware.

Site	Length	Operator	MCC:MNC:TAC	Cells	VRS	maxDist
AZ	6 km	AZ	240:40:333	5	4	<1 km
RV40	55 km	Telia Company	240:1:28	81	10	5 km

Table 12 LTE networks used in testing NPAD functionality.

The final version of the test setup was partly integrated to offer a self-contained experimental platform using a RaspberryPi based system with the Teltonika modem and UBlox F9B, see Figure 63. The compact formfactor makes it easy to integrate in different environments. During NPAD this system was once used in a test with Einride, see section 6.5.1.5.

Figure 62 depicts the logical flow of data using the setup. Cell information is collected by `cell_meas.pl` from either the AT layer (3GPP TS27.00x) or the proprietary control of the LTE modem. A WAN connection is also established through the same device, which is used to route data to and from the location server and allows other IP connectivity required by the host system. The cell information is forwarded to `supl2rtcm` which implements the SUPL/LPP communication to the location server and converts the resulting reference stream into a RTCM3 compatible data. A modified version of `rtcm3torinex`[35] converts the RTCM data to human readable Rinex3 and additionally measures latency and rate of the data distributed data. RTK clients can retrieve the regenerated data using a NTRIP caster compatible interface on the local LAN or WLAN. The setup also contains an internal RTKlib based client that can use external observations from connected receivers without RTK capabilities. The return data of a client may contain NMEA information about the clients PVT solution, including statistics about RTK fixing status and uncertainty measures, which together with the current cell information is parsed by `check_cells.pl` and is locally displayed or offered by a locally accessible http service.

From a practical point of view the immediate feedback of different parameters is important in a testing situation. The setup establishes for instance a control channel to a RISE server that can be used to interact with the setup at the OS level even in remote operation when integrated at a third party.

The system is GNU/Linux based using Ubuntu/Raspbian. Scripting is done in Perl/PDL, the SUPL/LPP stack and RTCM3 conversion `supl2rtcm` is based on a library supplied by Ericsson and Waysure implemented in C++, `rtcm3torinex` and `RTKlib`[36] are applications/libraries written in C.

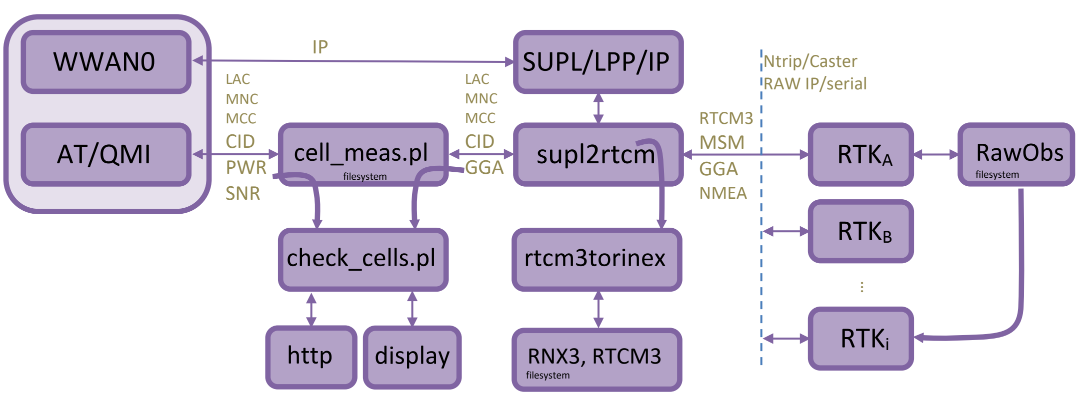


Figure 62 Relevant logical flow of the NPAD testing setup.

Figure 63 RISE compact ruggedized experimental NPAD setup (CERES[3]) is integrating a modem, the SUPL/LPP stack run on a RapsberryPi 3B+ and RTK with a UBlox F9P. A display gives immediate feedback about the state of the cellular network, VRS and RTK using either the built-in receiver or any other RTK client connected using Ethernet or wireless LAN. The local NTRIP Caster can either use cell or position-based access via SUPL/LPP, or offer a direct position-based access using an extern NTRIP caster. The device is also offering time services (NTP, PTP) based on the internal GNSS PVT solution to the connected Ethernet. The device is intended to be powered from a standard USB Power bank to be operated for a few hours.

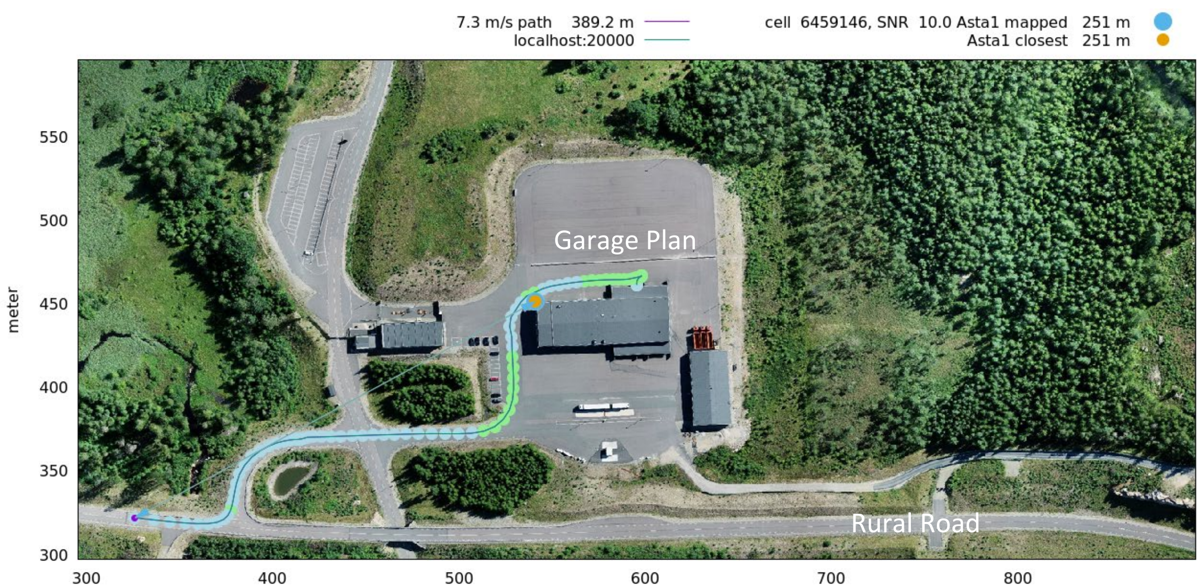


Figure 64 Typical visualization using `check_cells.pl` of tests using an overlay of a local high-resolution aerial photo of AstaZero using `gnuplot`. The scene shows the first few hundred meters of the access road to the Rural Road. Colored dots along the path indicate the cell that was used. The graph indicates the distance to the "cell-chosen" and geometrically "closest" VRS.

---

[3] Compact Ephemeral Ruggedized Experimental Setup or
Compact Ephemeral Rise Experimental Setup

6.5.2.2 Cell Dynamic Behavior

During various test occasions, the dynamic behavior of cell changes was studied. For the sake of simplicity, we assume that the user of a connected mode mobile handset (UE) is passive in the cell change mechanism [37] and that the UE/network tries to make an optimal choice from a communication point of view and triggers and subsequently performs a handover (HO). From testing it is obvious that the cell selection is constrained but is not necessarily always predictable or repeatable since the HO is based on UE power measurements of neighboring cells in a kinematic and varying environment. The load of the network and other parameters my hinder an intended HO and thus continued connectivity may fail. Also depending on the static mapping of cells to VRS:es, the VRS advertised may not always be optimally chosen. Cell sizes may both exceed (rural) or be much smaller (urban) than the mesh size of the VRS grid. Mapping is always a compromise and the discreteness of large cells and a ridged meshed VRS grid can lead to unintentional results. Furthermore, the network design is usually a business secret of the network owner and an implementor of an NPAD service in a location server should seek cooperation for gaining good knowledge of the cell coverage in order to optimally place VRS locations. Dynamic networks that change coverage have requirements on dynamical updates of the mapping.

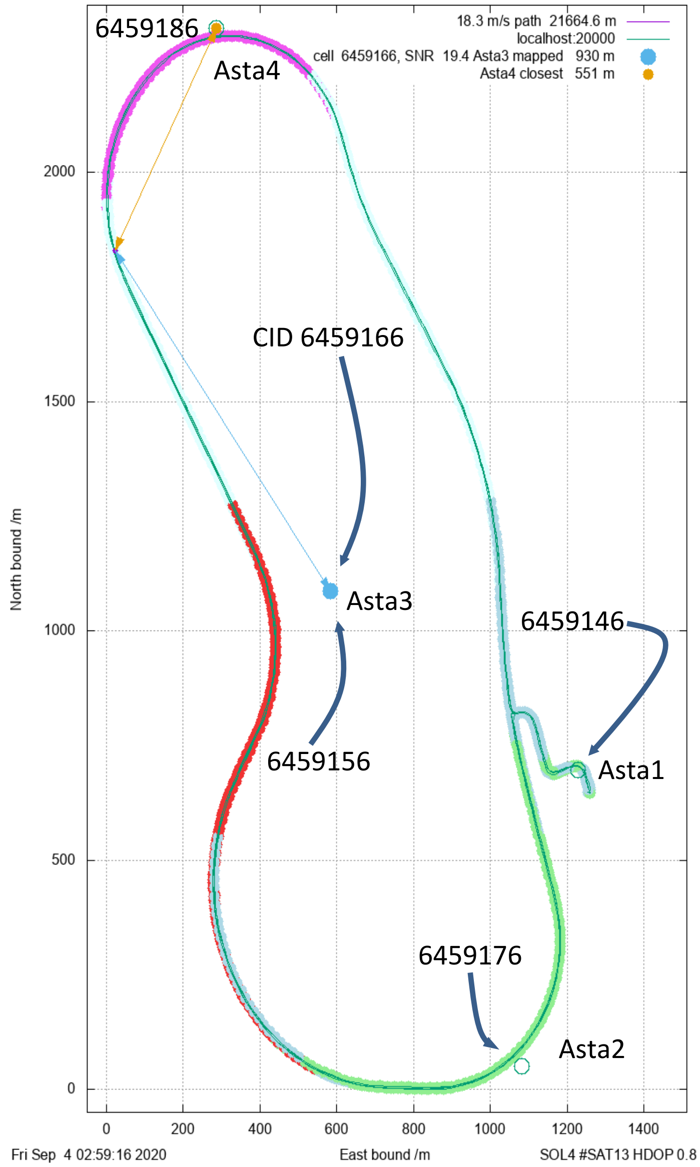


Figure 65 Trace of an AZ Rural Road test probing all five AZ cells. Mapping between cells and VRS were qualified by cell power measurements along the track. Experienced cells do not always coincide with the design. In the example the coverage of cell 6459166 and 6459156, both mapped to Asta3, is large on both sides of the track and close to cell 6459186 with mapping to Asta4.

For our tests cell information was collected along the tracks and mapping was based on the surveyed coverage and a set of predefined VRS locations. Figure 65 shows an example of the AZ cells seen along the Rural Road track. The situation depicted shows that mapping is slightly suboptimal.

Figure 66 shows a typical difference between a clockwise and a counterclockwise travel on that track and exemplifies potential differences in the cell selection depending on traffic situation.

The true NPAD solution intends to use SI broadcasting by the network control plane and a user thus strictly depends on the cell that the UE is connected to or listens to in idle mode. Unicast based NPAD, such as the use of SUPL/LPP, are on-demand IP services that more flexible in how and when to virtually switch VRS based on the current cell information and/or the user position. The user can learn the mapping by probing the network given the history of charted cells and depending on the collected statistics and possibly on the traffic situation decides when to switch context.

However, during the tests in NPAD the SUPL/LPP method was only intended to simulate broadcast distribution and very few governing rules were implemented. For instance, at some parts of the AZ track rapid cell changes with a few seconds interval between two cells can be observed. For this a time hysteresis is useful to avoid rapid context changes.

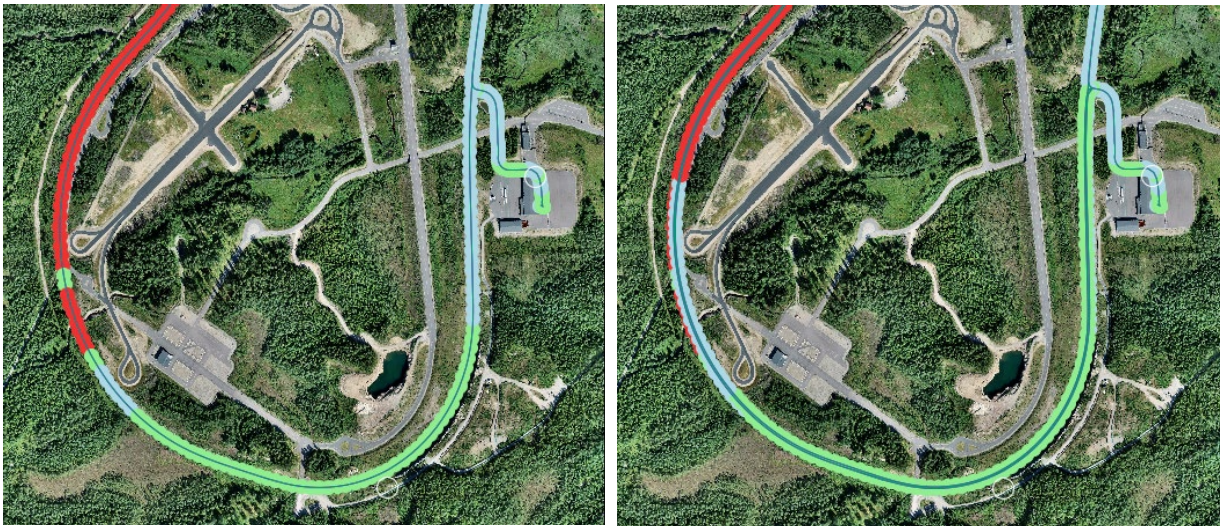


Figure 66 Clockwise (right) and counterclockwise (left) run on the AstaZero Rural Road systematically assigns different cells in certain areas of the track (especially south)

6.5.2.3 Limits on the VRS grid

A typical surveyor's use of Network RTK relies on the validity of the reference data supplied by the initiated VRS within a few hundred meters at most. The user usually requests an updated reference if the surveyed position changes. The on-demand N-RTK services usually also tracks the user position and changes VRS if deemed necessary in order to offer the best possible conditions.

The NPAD grid coverage, as described in 6.2.2.1, is chosen to balance scalability and end-user performance. Some empirical results are given in 6.2.2. The following summarizes a more general view on how the baseline between user and virtual reference statistically influences the user position estimate uncertainty.

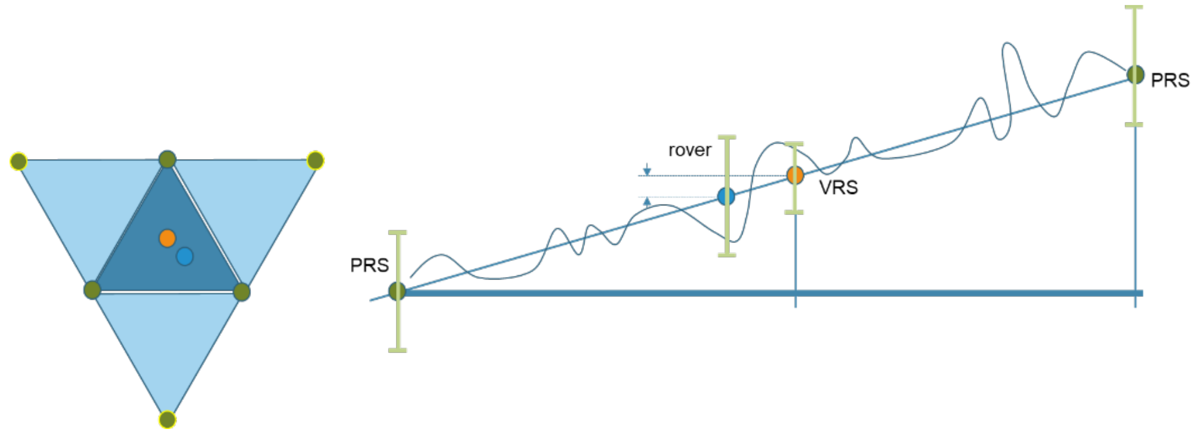


Figure 67 Simplified view of the one-dimensional tropospheric gradient estimate of Network RTK used to model atmospheric conditions at the virtual reference. Exaggerated depiction of atmospheric turbulence implies general limitations for positioning in kinematic real-time applications.

GNSS based estimation of user position and time needs to deal with several error sources. The double differential approach of RTK allows to eliminate the effect of all clock errors and minimize those created by orbit errors. Network RTK additionally estimates a plane[4] of the local atmospheric delay with the help of a set of adjacent physical reference stations, which is used to correct the observations at the location of the VRS, see Figure 67. However, NRTK cannot compensate for turbulent effects and additionally the baseline vector between user and VRS location introduces a baseline dependent error. The latter is a complex and geometrical error that is difficult to separate into its components. It is the sum of orbit errors mapping with baseline orientation and length, tropospheric gradient error estimates, the local environment around the physical references, and possibly systematic differential errors of the ionospheric models used for single frequency applications. Small scale turbulence of the atmosphere and the turbulent nature of the local environment around antennas, such as multipath, add additional uncertainties to position estimates with RTK. Table 13 summarizes the effects of the different error sources, Figure 69 shows an example for the RMS statistics of the baseline dependent positioning error.

Optimal RTK positioning is achieved in situations when the rover RTK engine can estimate the carrier phase ambiguities fixed to integer quantities. Often a combination of double differenced code and carrier phase observations is used where the dominating code noise is suppressed by integration over time. In order to robustly succeed with ambiguity fixing, the errors introduced by unmodeled atmosphere and the local environment must be within certain limits. Errors caused by turbulence govern the accuracy of RTK with collocated VRS, i.e. zero baseline. Most prominent is the influence of the ionosphere under difficult conditions during the maxima of the solar cycle, but also single solar incidents make it sometimes difficult to optimally use RTK, especially during nighttime and at higher latitudes in Europe, such as northern Sweden, see Figure 68 for an example

[4] Often linearized, but more complex approximations possible

Error Source	Constant	Turbulence	Baseline induced
Sat Clocks	✓ SD==0		
Sat Orbits			✓
Ionosphere		✓	✓
Wet Trop		✓	✓
Dry Trop			✓
Local Ref VRS		✓ averaged	✓
Local Rover		✓	
Receiver Clocks	✓ DD ≈ 0		

Table 13 Main error sources for RTK users. Satellite clocks are eliminated in common view of single differences, receiver clocks in double difference typical for RTK.

of assessing ionospheric activity for the purpose of surveying. Under normal conditions, biases and small-scale variations of the troposphere, mostly the wet delay, can hinder proper resolution of the ambiguity. The local environment around the rover antenna may however be the most limiting factor for good positioning accuracy with RTK. Fast changing code multipath may inhibit initial fixing and re-fixing in kinematic situations.

The design of the NPAD grid on the service side, and the type, placement and integration of rover antennas on the user side are the primary engineering parameters to assure functional RTK for transport applications. Assuming fixed ambiguity conditions, the combined statistical user positioning error is a combination of turbulent and baseline dependent errors.

Table 14 gives a qualified example for the statistical error budget of a 30 km NPAD mesh with maximum 15 km baselines between rover and grid VRS. Such a large sized grid roughly matches the current grid of PRS established in SWEPOS and requires about 600 VRS to equally cover the country. A 5 km grid on the other hand requires to establish about 4500 VRSs and statistically gains about 7 mm in uncertainty.

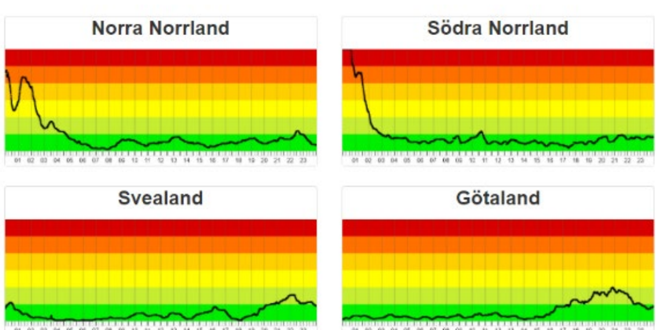


Figure 68 Ionosphere monitor by SWEPOS assesses the probability of successful ambiguity fixing depending on the area of service in Sweden from North to South, from top right to bottom left. Red indicates difficult ionosphere with low probability of obtaining an integer fix, green indicates good ionospheric conditions and high probability for a fix. https://swepos.lantmateriet.se/services/iono.aspx

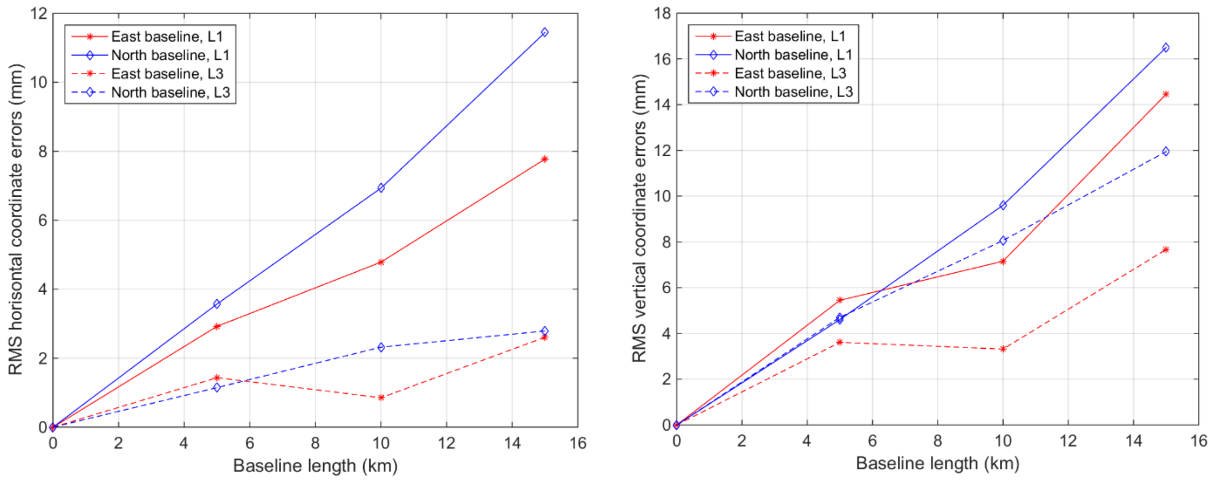


Figure 69 Empirical example of positioning errors for differential positions between a SWEPOS PRS at RISE Borås and several VRS placed 5, 10 and 15 km for north and east oriented baselines. To the left RMS statistics for the horizontal plane, to the right for the vertical component.

Error Source	Constant	Turbulence		Baseline Length related	
		Horizontal	Vertical	Horizontal	Vertical
Sat Clocks	0			1/km	1.2/km
Sat Orbits		1	2		
Ionosphere		7.6	11.7		
Wet Trop		3.7	14.8		
Dry Trop					
Local Ref VRS		0.9	1.4		
Local Rover		3.5	5.6		
Receiver Clocks	0				
Total (mm) 15 km		9.2	19.8	17.6	26.8

Table 14 Example of an uncertainty budget for RTK positioning with a good rover setup during mean atmospheric conditions. A 15 km baseline would pose a one sigma horizontal uncertainty of about 20 mm, and 30 mm for the vertical component. Difficult rover environment may however be the most limiting factor for the use of RTK in automotive applications.

6.5.2.4 RTK Aspects

Coordinate systems

The use of RTK offers a direct access to an established coordinate system. RTK position estimates are in principle baseline estimates between a rover antenna phase center and the published coordinate of the NRTK virtual reference. In the case of NPAD the VRS grid is derived using the SWEPOS network in Sweden which maintains its coordinates in a reference frame called SWEREF 99 [38], which is a realization of the European reference system ETRS89. ETRS89 is an Earth-Centered-Earth-Fixed (ECEF) geodetic cartesian reference system with a quasi-static Eurasian plate, eliminating the effects of continental drift in maps and surveying. ETRS89 coincides with the International Terrestrial Reference System (ITRS), realized as the ITRF and in proximity equal to the WGS84, in1989.

The agreement of a coordinate system with the physical world is an essential property for many applications, such as autonomous transports or cooperate ITS. Positioning often relies on a combination of different positional sensors, where GNSS is only one of several. In a practical use of GNSS, position estimates may be derived using several methods such as point positioning (SPP, PPP) or different forms of differential positioning (DGNSS, RTK). This can cause the position estimates to refer to different reference system, consequently systematic differences must be dealt with. In a typical NPAD scenario a proper RTK solution can for various reason not always be calculated and the positioning engine may eventually fall back to single point positioning estimating positions in WGS84 rather than SWEREF 99. These systems drift with about 20-25 mm per year which currently amounts to about 0.7 m. For the conversion of coordinates estimated in ITRS/WGS84 to an ETRS89 coordinate a multi-parameter similarity transformation [39][40] must be applied.

Network Harmonized Carrier Phase Integer Ambiguities and VVRS

The VRS changes along a NPAD augmented track may cause several problems for an RTK user. The following is argued in a context of a positioning system dominantly relying on GNSS.

If we assume a kinematic integer fixed positioning solution of an NPAD RTK user, then a change of a virtual reference station would supply a new set of reference observations to the RTK engine. Positioning is made aware of a new reference position and should normally be able to great extend geometrically adapt to the new baseline. In addition to network-side errors introduced by the new baseline, see the previous chapter, it also must handle reference carrier phase observations that potentially have a different carrier phase cycle relation. For an unaware RTK engine this would immediately break the current set of ambiguity parameters and loose the current fixed solution and require restarting the fixing process, which takes some time for the rover to perform. During that time unreliable positioning information may cause problems for upper layer positional/navigational estimation. The problem can be eased with different methods, such as concurrent RTK engines working with a multiple set of reference data. NPAD does not explicitly excludes this approach as the standards set forward by 3GPP offer at least two reference data streams to concurrently be broadcasted.

One obvious solution is to offer a harmonized subsets of carrier phase observations. If neighboring VRS can be harmonized to agree in their carrier phase relation for at least a subset of the overall observations, then a rover has a good chance to retain the integer fixed solution. 3GPP release 16 has rudimentary support to relay information about the state of harmonization between cells. A NPAD aware RTK engine can use this to support the VRS context change. Additionally, custom RTCM3 messages can be crafted to carry fixing information. A network solution of a large number of VRS is a complex task and should in principle be part of the Network RTK software itself as it already handles all PRS data. However, today this functionality needs be implemented at the interface between VRS grid and location server. The project has experimented with different methods to harmonize VRS carrier phase observations that may be used to integrate into such middleware. The quality and stability of the underlying physical reference network creates optimal conditions for robust ambiguity resolution for VRS baselines up to 5 km.

Similar to the problem of ambiguity mismatch between two VRS the change of a baseline vector alone may be confusing for a simple RTK engine and can therefore cause a time consuming reinitialization of the positioning solution. For simplicity the network may combine a number of nearby VRS into a single virtual VRS (VVRS) that retains the localness of its observations at the VRS positions, but virtually refers to a single remote reference position. The tight VRS grid by itself is retained and offers good atmospheric approximation at the user position. The VVRS incarnation of the local VRS is geometrically corrected to a common reference point and a user need not to be aware of a change. This of course assumes ambiguity harmonized observations of all the VRS within a VVRS. Such a construct has however limitations in the length of the achievable baseline mainly caused by differential orbit errors projecting onto the geometrical correction of VRS observations. VVRS-sets covering a local urban area could help to avoid many context changes and possibly improve the availability of GNSS position estimates for many NPAD users.

It should be noted that VRS context changes usually pose the lesser of problems an RTK user may experience. A receiver's total loss of lock, due to tunnels or bridges, is clearly more difficult and time consuming to recover. After requiring satellites, the RTK engine must start to estimate all parameters from scratch. Tight coupling of inertial sensors may improve such situations.

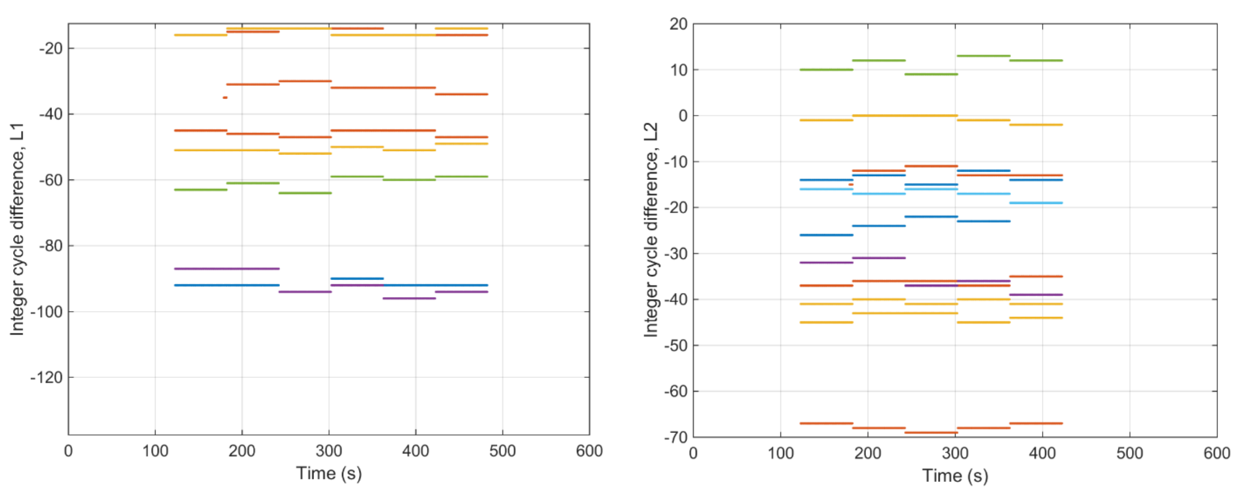


Figure 70 Example of GPS L1 and L2 ambiguity parameters between different SWEPOS VRS placed with 5 km from a rover at RISE at intervals of 60s. Colors indicate the same GPS PRN. The VRS all use the same dominating PRS. Differences can be in the order of 10 cycles.

6.5.2.5 Future Work

The research and development achieved during NPAD has shown the potential of a scalable distribution of augmenting GNSS data to mass-market applications. From the perspective of an NMI the possibilities of NPAD as means of providing a distribution channel for traceable measurements is obvious. NRTK allows access to a reference coordinate system and may also be used to distribute traceable time and frequency if VRS observations are corrected for their local clock errors relative to time calibrated PRSes. Today SWEPOS includes receivers connected to UTC(SP) which can be used to provide traceability of VRS timing to UTC.

Future work related to NPAD includes the concept of a combined middleware allowing to harmonize VRS carrier phase ambiguities, formation of VVRS entities and the introduction of UTC(SP) traceable timing in the (V)VRS observations. The latter also requires improved RTK rover algorithms that can resolve position and time.

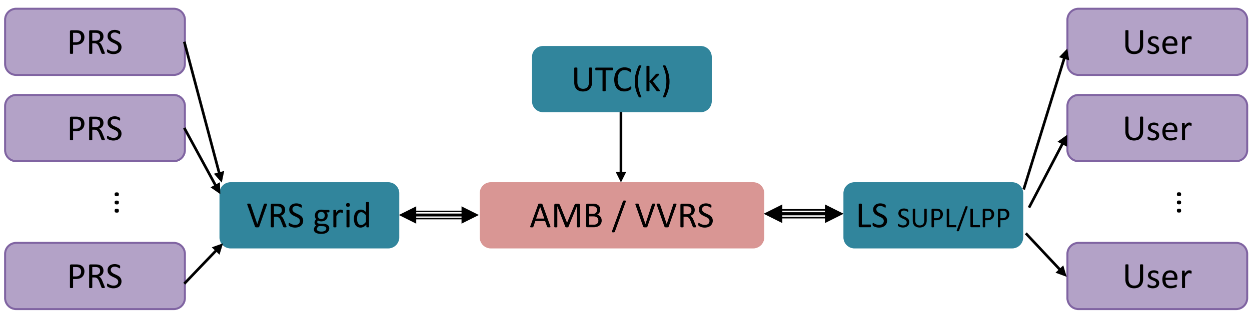


Figure 71 Middleware acting as a network ambiguity resolver, super VRS and health monitor for the VRS distribution to the locations server (LS)

6.5.3 Integration of SUPL/LPP on AstaZero

This section describes the integration of the SUPL/LPP stack in a 4G modem at AstaZero. This work was a late addition to the project, not specified in the application. AstaZero saw an opportunity of integrating the client side of the NPAD-solution to support the availability of the developed system at the test track. Due to the reduced need for testing on AstaZero, it was decided on a project level that AstaZero could contribute to usage of the NPAD-solution. This resulted in an adaption of the SUPL/LPP client described in section 6.6.4.1 which was implemented and used on a 4G modem at AstaZero.

The following section describes the background and motivation this work, the hardware and software setup used, and the desktop demonstration setup.

6.5.3.1 Background

Supporting customers and research projects in development of future transport systems is a priority for AstaZero. This is normally done through access to a realistic traffic environment, where systems can be tested before it is released to open market. In this project the need for scalable and accurate positioning systems have been investigated, and a support system for RTK-based positioning have been developed to support, herein referred to as the NPAD-solution. AstaZero has identified that to support this development, the same system developed in this project must be available within the traffic infrastructure on the test track.

Vehicles equipped with an RTK-based positioning system currently relies on local RTK-base stations for GNSS reference data. This system supports the ongoing testing at the test track and is well suited for small-scale testing of vehicles and its functions. With the introduction of more connected and automated vehicles at the test track, there will be an increased need for the support systems which the vehicles rely upon in the real traffic environment. Thusly there is a need to upgrade the supporting infrastructure at AstaZero.

The private 4G network installed at AstaZero provides its customers with connection between vehicles and access to the internet. This is done through the use of 4G modems, available for usage at the test track. A common variant of 4G modems available at AstaZero is the Spectre v3 LTE modem. Running a lightweight Linux distribution, it has the capability of running scripts and custom programs, while providing a consistent connection. This enables the user to integrate protocols which are under development and support the usage of new support systems by converting the new protocols to old and integrated protocols, allowing the exploration of the new protocols quicker.

6.5.3.2 Purpose

The purpose of this developed software is to enable access of virtual reference stations available on the Location Server through the modem for positioning application which does not support the SUPL/LPP protocol used by the server. The objective of the modem software is to negotiate the change of VRS provided by the Location Server by providing the current modem Cell ID to the server. This enables pre-existing solutions on the test track to be able to use this service on the test track, without the need for additional integration.

6.5.3.3 Hardware

The hardware used for the integration of the SUPL/LPP stack is a Spectre v3 LTE modem, as shown in Figure 72. Using a custom sim-card provided by AstaZero, the modem could be connected to the private 4G network at AstaZero. The modem has built in support of running python scripts and can be accessed through either of its two RJ45 ports and through the USB port. Only the RJ45 port were used for the project.

Figure 72 Picture of the Spectre v3 LTE modem used for SUPL/LPP integration. The application developed is run on this device, which in turn is connected to the private 4G network at AstaZero.

6.5.3.4 Software

The software is divided into two parts, the SUPL client which is explained in 6.6.4.1 and an NTRIP server. Both parts are hosted on the Spectre v3 LTE modem, where the SUPL client handles the connection to the Location Server and the NTRIP server handles connection of any GNSS based positioning device requesting RTCM data. The Cell ID is available for the SUPL client through a modem specific API.

Figure 73 shows the software components used within the 4G modem and how they interact with each other and the outside world. The SUPL client, which is the same as the one described in section 6.6.4.1 can access the current Cell ID and use it to negotiate with the Location Server about which VRS to use. The data stream provided from the Location Server to the SUPL client is then used by the NTRIP Server software component. A user, or in this case a GNSS based positioning device can simply use normal NTRIP client software to access a mountpoint, where the data from the cell specific VRS can be received.

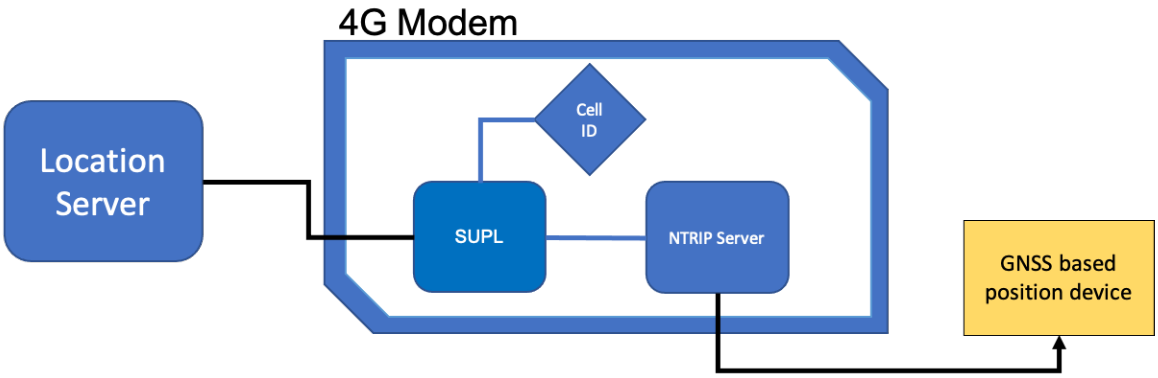


Figure 73 Software components illustrated together with hardware. The software components are running on the Spectre v3 LTE modem, which handles communication to the Location Server.

6.5.3.5 Desktop Test Setup

To test the hardware and software setup, the system was tested in a desktop test setup. Due to corona restrictions and limitation in available GNSS based position devices, the tests were restricted to a desktop setup. The setup for these this test is depicted in Figure 74. According to the figure, a laptop with the open-source program ntripclient [13] was used to emulate a GNSS positioning device connecting to the modem. The SUPL/LPP software with NTRIP server is run on the 4G modem with a static cell-id preprogramed, since the 4G network is restricted to AstaZero only.

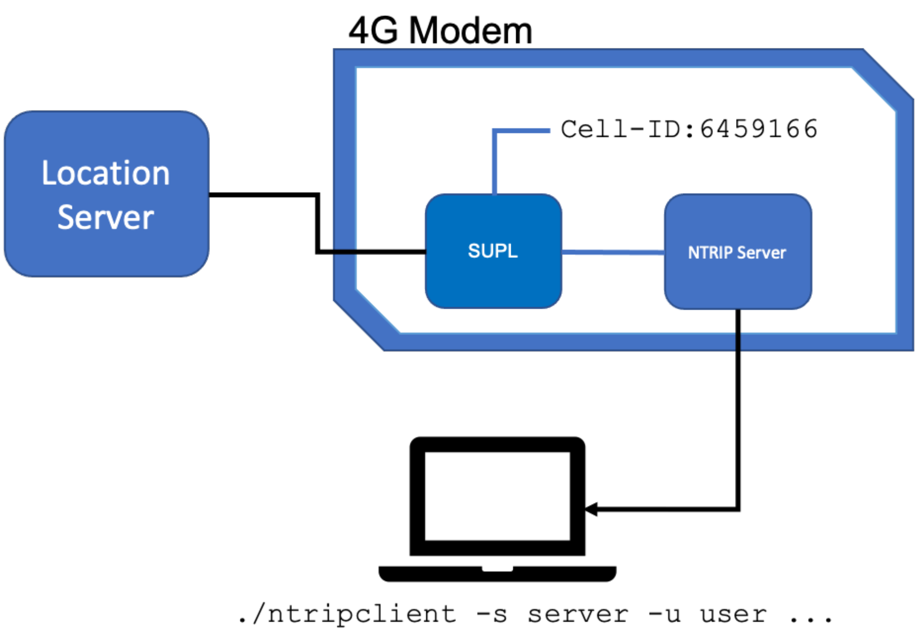


Figure 74 The desktop test setup which was used during the project.

A laptop with the open-source program ntripclient was used to emulate a GNSS based positioning device. The SUPL/LPP software with the NTRIP Server component was run with a static Cell-ID, representing a real Cell-ID on the test track.

6.5.3.6 Future Work

Due to memory limitations in the 4G modem, problems occurred during the deployment of the developed software. The modems would occasionally become idle and stop working altogether during deployment. There is therefore of interest of exploring a reduced version of the developed software, which occupies less system memory.

The integration of this software remains untested together with a GNSS based positioning unit. It is of interest to explore the outcome on the position when the modem automatically replaces an old VRS with a new one in the data stream. At AstaZero there are a number of high-performance positioning units, such as the RT3000 unit [14] sold by Oxford Technical Solutions which would be interesting to test with this developed software. Combining this with the validation of positioning, which is explained in section 6.6 is especially of interest.

6.6 Validation of Positioning

Positioning can be separated into relative positioning and absolute positioning. Validation of these types of positioning range from checking that an AD vehicle parks within a set of lines as intended, to comparing vehicle INS against a standalone IMU-GNSS system. The comparison against a standalone IMU-GNSS system is somewhat of a golden standard in automotive testing of positioning. Within NPAD one part of positioning validation has been to validate these types of absolute positioning systems with metrological traceability [15] and a known measurement uncertainty [16]. In short this implies measuring the vehicle position relative to a measurement system with a known position in a global coordinate system, such as WGS 84 or SWEREF 99.

At the start of the project an ambitious goal was set to create a reference system that could validate IMU-NRTK-GNSS absolute positioning during movement with comparable or better performance. It was quickly discovered that no commercial system existed that could perform at a level that was significantly better and fulfilled traceability requirements, detailed in D4.4. There were a few commercial systems that could approach similar performance within a limited measurement area, such as LocataLite [17]-[20], iGPS [21]-[24] and various motion capture systems [25]-[29]. These systems all had some form of limitation that would exclude them from use in the project. Therefore, the approach was shifted towards using established measurement systems within metrology and incorporate them as a part of the larger reference network being developed on AstaZero called A0REF described further below.

6.6.1 Methods for validation of positioning systems

During the project several different methods for approaching validation of positioning systems were identified and evaluated in some way. Three approaches that were tested are described below.

6.6.1.1 Laser tracker as a reference

Among the commonly used optical instruments today the most accurate are interferometers and absolute distance meter. These are often incorporated in laser trackers together with precise angular encoders for accurate coordinate measurement. Laser trackers are used at short distances, typically below 50 m, where many points need highly accurate measurement. They have excellent accuracy when measuring stationary points, but they encounter problems when trying to accurately track and measure the distance to an object at the same time. To put it simply, when an object is moving at high speed the target is not in the same place long enough for an accurate measurement to be taken. Laser trackers can measure the position of moving targets but are limited in speed, distance and the field of view of the retroreflector they measure against. It is also limited to tracking a single point, but excel at this task, for example it outperforms iGPS systems as soon as the speed increases [24]. In kinematic testing at speeds of up to 6 m/s three different Laser trackers were found to have sub-mm errors [30]. One major drawback for use in automotive testing is the sensitivity of the equipment with regards to environmental conditions. Normally they are used indoors in production- or lab environments and any deviation from such conditions affect the performance of the equipment.

Due to the limitations listed above a laser tracker could at best be used as a reference system at lower velocities. Within NPAD a laser tracker was used in tests in outdoor environments to evaluate its limitations for future use.

6.6.1.2 Heading comparison against total station

Total stations, like laser trackers, incorporate an absolute distance meter with accurate angular encoders. When measuring objects at great distances with high precision a total station is the equipment chosen. They do however lack the ability to measure moving targets and are widely used in geodetic surveying, construction and monitoring of stationary points.

Therefore, a total station can be used to place and relate equipment and objects in various reference frames. In automotive positioning it is possible that it can be used as a reference for an INS when stationary. Within NPAD a total station was used as a reference in evaluating the global heading of a vehicle.

6.6.1.3 NRTK-GNSS measurements of known baseline on vehicle during movement

An approach that completely avoids the need for an external system tracking the vehicle is to bring a reference with you when driving and comparing your solution against the reference. This is in practice done by mounting antennas on a rigid platform with a known baseline between the antenna mountings. This baseline becomes the reference and can by calibration supply the user with both metrological traceability and a quantified measurement uncertainty to compare measurements against.

The drawback of this method is that it in practice is a one-dimensional length measurement by taking the difference between two NRTK-GNSS solutions, which themselves are absolute positioned relative to the base station or VRS in use. Any positioning errors are likely to affect both antennas similarly which might result in the illusion of an accurate measurements while they might be equally wrong in terms of absolute positioning and still deliver an accurate baseline measurement. Therefore, this method might be limited for use as a health indicator of an INS with dual GNSS antennas, or to detect severe degradation that affects the antennas differently.

6.6.2 Positioning Reference System

6.6.2.1 A0REF - A local reference network

At the beginning of NPAD the partners RISE, AstaZero and Lantmäteriet had already planned on constructing a network of truss mast base stations for NRTK-GNSS corrections at AstaZero. The idea was that the masts mounted in bedrock could act as reference points for research in positioning. The masts would get their position in global reference frames from GNSS while their stability could be monitored with geodetic equipment. In addition, the masts were fitted with retroreflective mounts aiding in monitoring their stability, position relative each other and relating any object or reference equipment to the masts, and in turn global reference frames.

With the finalization of NPAD three base stations are installed and a fourth is under investigation. Out of the three active A0REF masts one is live in the NRTK-GNSS service SWEPOS and is a useful addition for AstaZero as there previously were no SWEPOS stations close to the test tracks. The remaining two are recording and storing data but are not in use in the live service. Two of the masts as well as the retroreflector mounting on the masts are shown in Figure 75.

Figure 75: Photos showing the retroreflector mounting below the antennas (left), southern mast which is part of SWEPOS (middle) and the mast next to the high speed area control tower.

One of the future intended uses of A0REF is to connect metrologically traceable relative measurements of moving vehicles on AstaZero to global coordinates, to validate absolute positioning systems. This is illustrated in Figure 76, where measurement systems, $S_{1\text{-}4}$, are positioned on the track in relation to A0REF by total station and local reference points. This relation is measured with great precision and metrological traceability, relating measurements inside the local measurement area to global reference frames.

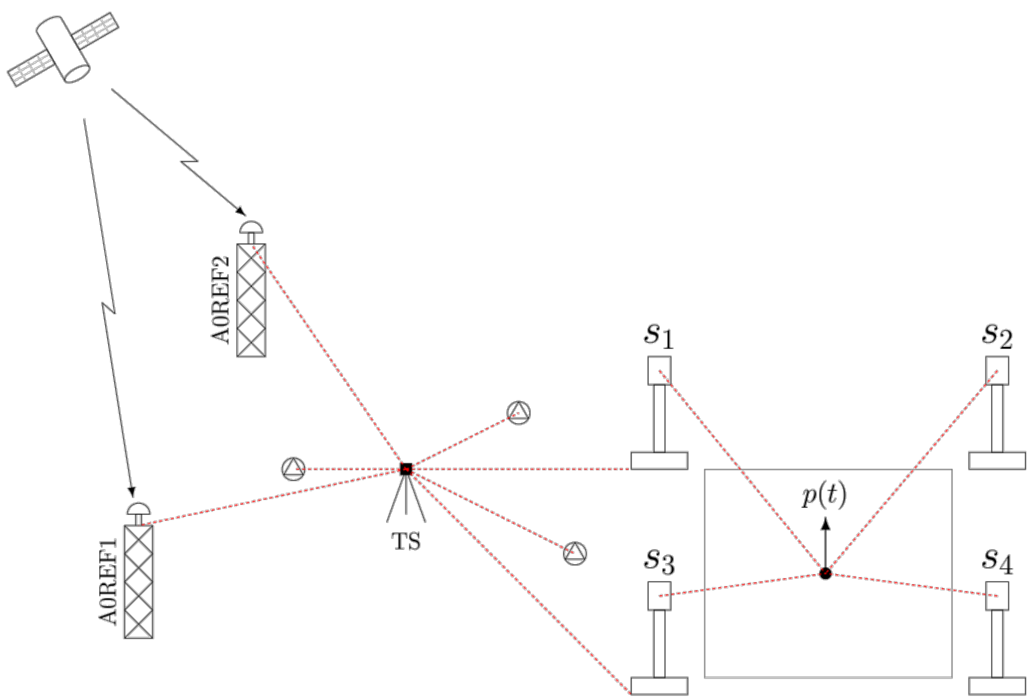


Figure 76: Illustration of how measurement systems ($S_{1\text{-}4}$) could be related to A0REF, which in turn has a known position in SWEREF 99. The red dotted lines are measurements with metrological traceability.

6.6.2.2 A0REF initial measurements

During the spring of 2020 local reference points were installed around the A0REF masts to aid in future measurements and this was followed by the first stability measurements of the masts, a laser scan from this is shown in Figure 77 as an excerpt from the measurement report [31].

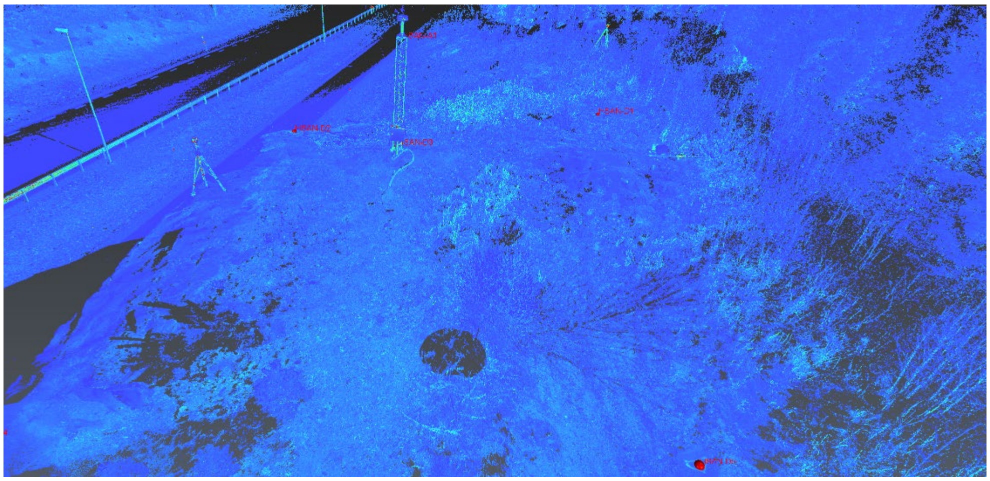


Figure 77: Point cloud view of the northernmost A0REF station at the north end of the high speed area at AstaZero.

This first round of measurements does not prove the stability but is the first important step in the long-term investigation of the mast's stability.

Two field studies were also launched during the summer and autumn of 2020 to develop approaches and investigate measurement uncertainties when measuring the distance between the two northernmost masts retroreflective mountings. These field studies only consisted of few measurements and determined the estimated distance between the two retroreflective mountings to be 633.245 m with an expanded measurement uncertainty of ±4.5 cm (95%), corresponding to a relative uncertainty of 0.71%. Which can be compared to the calculated 3D distance between the GNSS antennas on the masts from SWEREF 99 coordinates supplied by Lantmäteriet, which was 633.239 m [32].

The agreement between the retroreflective mountings the antenna distance is a first step, but more work is needed to make the measurements directly comparable. These initial results are however very promising. It is also estimated that the measurement uncertainty is grossly overestimated and can be significantly lowered from what was learnt during the field studies.

6.6.2.3 Experimental platform for relating measurements to A0REF

Any potential measurement system would need to relate to a specific point on the vehicle to track over time in some way. This can be a black and white marker, a specific well-defined object or other distinct feature. In the case of a laser tracker being used it would be a spherical retroreflector placed on a magnetic mount. The mount itself need to be installed easily on any vehicle which navigation system is to be tested. Any positioning system to be validated would have to be related to the retroreflector in some way, which would be simplified if they have a known relation to each other beforehand. This led to the creation of an experimental platform, see Figure 78.

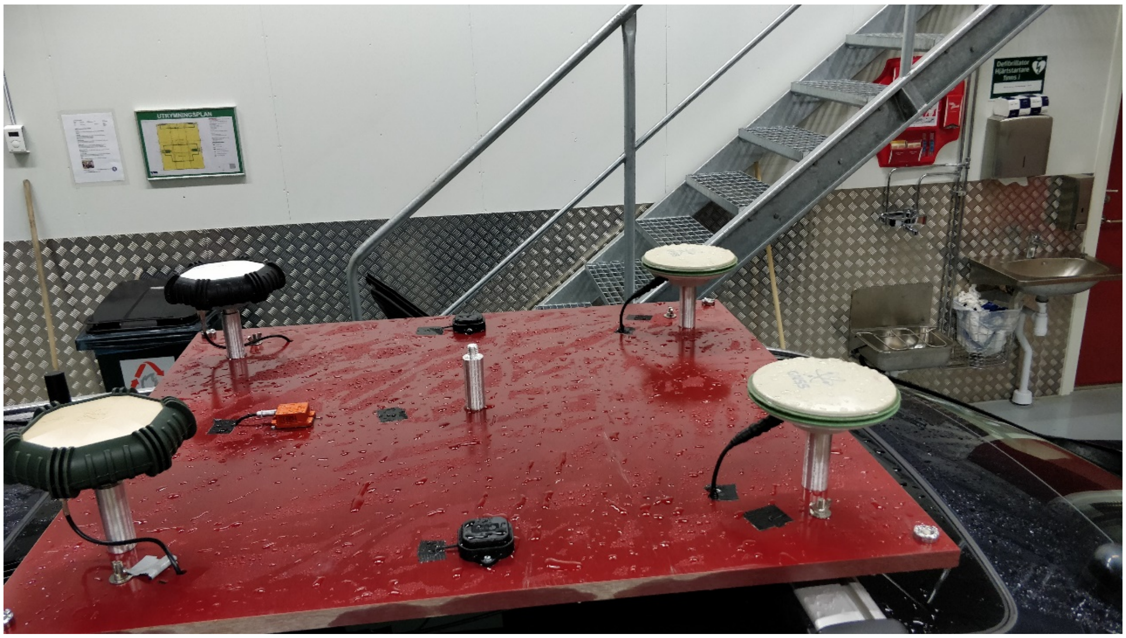


Figure 78: The current design of the "Leaf" platform, here fitted with 4 geodetic antennas, 2 patch antennas, one IMU and 4 retroreflector mountings. Photo from tests in November 2019.

The platform itself is simplistic but can with few adjustments be fitted to any vehicle with roof rails. It supplies the vehicle with five standardized threads for fitting of geodetic quality antennas, two u-blox patch antennas, one IMU and four retroreflective mountings.

6.6.3 Results from evaluation of positioning accuracy

6.6.3.1 Laser tracker limitations

To estimate the laser tracker limitations in outdoors daylight conditions tests were performed with a Leica LTD-800 laser tracker at RISE in Borås 2020-05-20, see Figure 79. Two vehicle paths, one linear from the laser tracker and one tangential passing by the laser tracker were performed with vehicle nominal speeds ranging from 10 to 50 km/h. The vehicle was fitted with the experimental platform and a retroreflector. A more detailed description of the setup and results can be found in the experiment report [33].

Figure 79: Laser tracker Leica LTD-800 during outdoor testing and test vehicle fitted with the experimental platform in the background.

The results from the tests indicated that a reliable distance for laser tracker measurements in favorable outdoor daylight conditions was in the range of 20-30 m, while the maximum measured distances were 54.9 m when moving and 63.1 m while stationary.

The maximum radial velocity measured was 28.8 km/h and the maximum tangential velocity measured was 31.3 km/h, both maximum values exceeding the equipment specifications. It was however noted that excessive acceleration can cause loss of tracking and that the tangential velocity contains far more noise due to encoder jittering as they track the moving vehicle, clearly visible in Figure 80 and Figure 81.

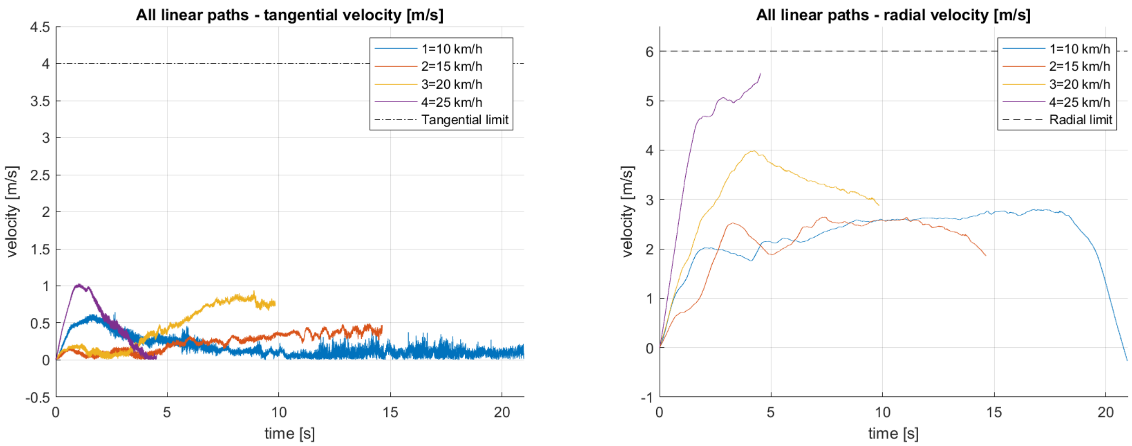


Figure 80: Laser tracker velocities for the 4 linear paths together with the spec. equipment limit.

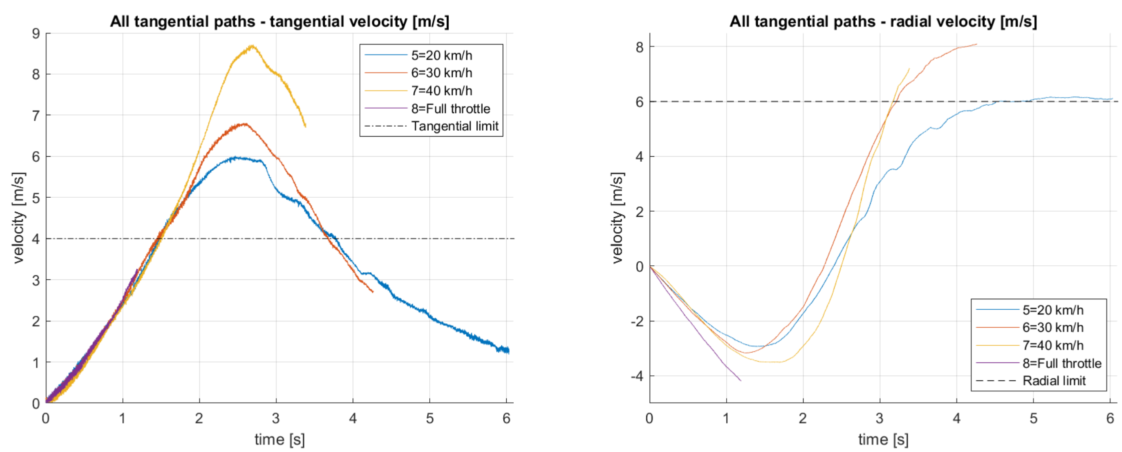


Figure 81: Laser tracker velocities for the 4 tangential paths together with the spec. equipment limit.

6.6.3.2 Heading comparison against total station

When the experimental platform was constructed some initial tests were performed at AstaZero where the stationary heading was compared for different systems and against a total station. The motivation for using a total station was that it's orientation in the world could be determined with a low uncertainty by exploiting NRTK-GNSS positioned references placed far from each other to get a more stable global heading estimation for the total station than what could be achieved on the vehicles from their short antenna baselines. Once the total station heading was determined, the internal angle encoders were accurate enough to be more reliable than anything on the vehicle.

The experiments were conducted in November 2019 at the AstaZero test tracks: high speed area (HSA) and rural road (RR). The test procedure consisted of measuring in the vehicle while stationary, driving around on the track with varying paths and speeds and then return to the measurement area, when stationary with a slightly different angle new measurements were taken. This was repeated 10 times on each test track. Phots from the test are shown in Figure 82.

Figure 82:Photos showing the total station heading setup on HSA (left) and the retroreflector used when placed in one of the mountings on the experimental platform during tests at RR (right).

In the tests an OxTS RT3000 with patch antennas was compared against u-blox F9P receivers mounted on test & development Arduino platforms. The F9P receivers were connected to Leica LS10 antennas on the HSA tests and u-blox ANN-MB-00-00 on the RR tests. The heading was also measured with total station by a retroreflector placed on the platforms mount points. The OxTS could directly output a heading while the F9P data was used to compute a mean position for each antenna for the duration of being stationary and then a heading was derived from these solutions. The F9P solutions were computed with the software RTKLIB and/or u-center.

As can be seen to the left of Figure 83 the stationary heading results agreed well with the total station when under an open sky as found on HSA. There was however an almost constant offset which could be due to misalignment between the orientation of the OxTS system and the experimental platform. The change in this offset in runs 8-10 was not determined and would require more testing as it could be caused by several factors.

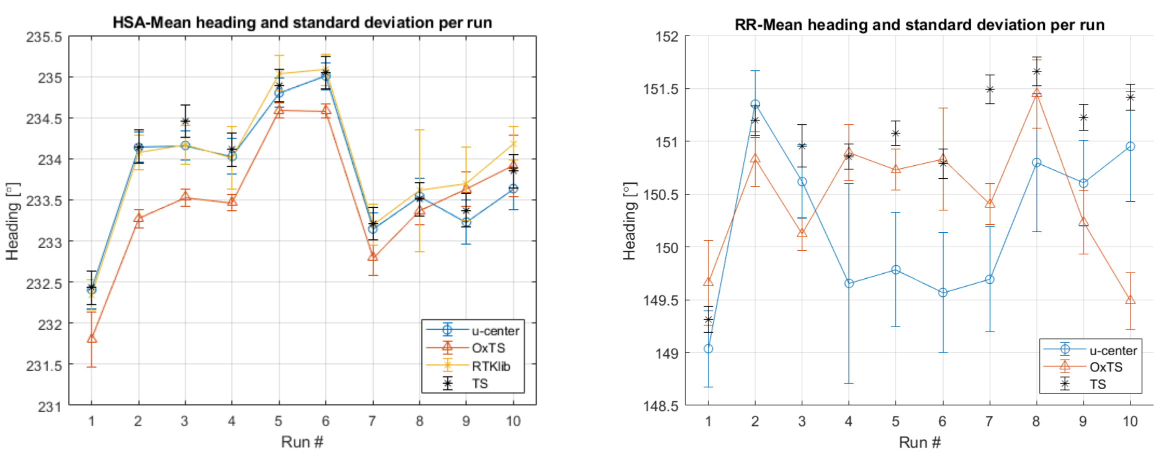


Figure 83: Mean heading of the vehicle measured with total station (TS), Oxford system (OxTS) as well as dual antennas processed in the software u-center and/or the open source software RTKLIB.

In the RR test, right in Figure 83, RTKLIB solutions for the heading could not be computed, therefore excluding it. The reason for this was that the measurement area closely represented an urban canyon, with trees blocking the sky in the south, resulting in many satellites being obstructed. Here the OxTS indicate a larger variation in its standard deviation and even agrees better with the total station than the u-center solution from the F9P data. The large variation and disagreement of the F9P data with the total station is most likely due to the lower grade antennas and the obstructed sky.

The results from these tests suggest that if further measurement uncertainty analysis and corrections for offsets between the system and the experimental platform would be performed it could probably act as a reference for validating heading estimation while stationary.

6.6.3.3 NRTK-GNSS measurements of known baseline on vehicle during movement

From the data collected in the initial tests with the experimental platform in November 2019 the baselines on the antenna mountings of the platform were investigated as references to be used. The data from the test described in section 6.6.3.2 was reanalyzed in terms of calculating the 3D distance between the antennas and comparing it against the baseline. The solution was calculated by u-center from the F9P receivers with Leica LS10 antennas on HSA and with ANN-MB-00-00 antennas on RR. The baselines were not calibrated beforehand as such only the nominal values of the baselines were known. For the tests for the tests on HSA the baseline was 0.6 m while the baseline of the patch antennas on RR was 0.74 m. The baselines were calculated from the complete series including during movement and while stationary, seen to the left and right respectively in Figure 84 and Figure 85. The stationary data is a calculated mean distance with one standard deviation error bars for each run.

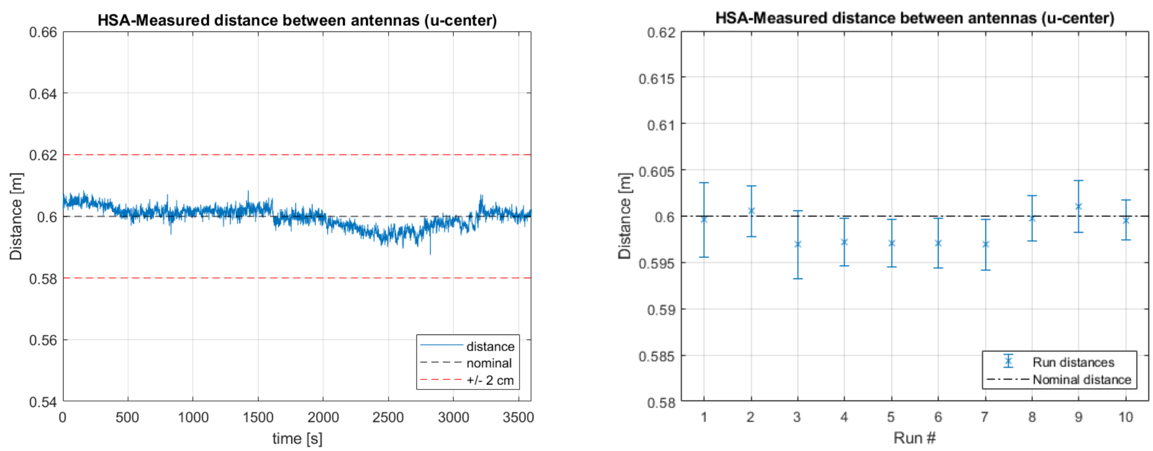


Figure 84: Measured antenna baseline between the Leica LS10 antennas during movement (left) and while stationary (right) when driving on HSA with good sky visibility.

The degradation in performance between the two tests is most likely caused by the lower grade antennas and worse sky visibility on RR compared to HSA. To draw additional conclusions the baselines would need to be calibrated and the test repeated with both low- and high-grade antennas measuring simultaneously.

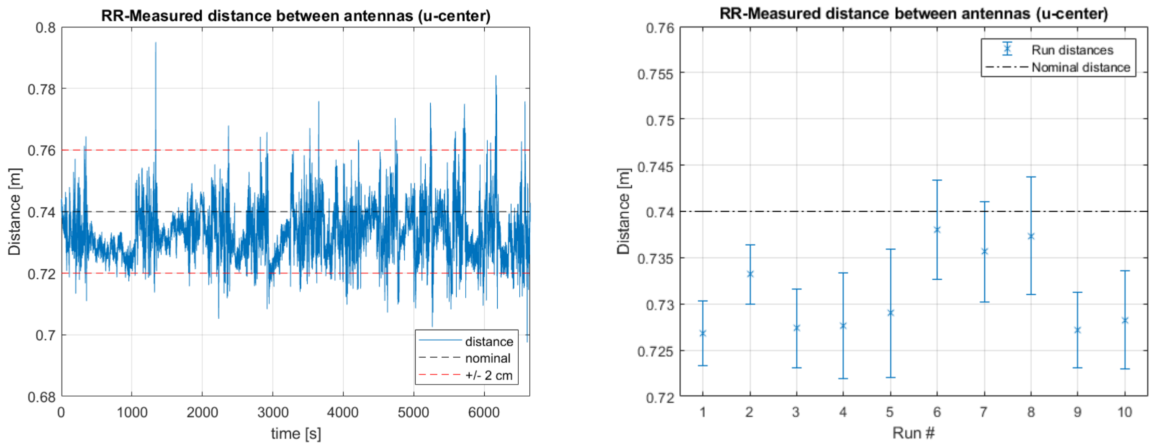


Figure 85: Measured antenna baseline between the u-blox ANN-MB-00-00 antennas during movement (left) and while stationary (right) when driving on RR with degraded sky visibility.

6.6.3.4 Future work

There is a lot of challenging work remaining after the conclusion of NPAD. The main work remaining is the installation of the fourth base station that will mark the completion of the first iteration of A0REF. Once this is done more field studies need to be made to establish measurement methods and relations between all masts to maintain the system to monitor its stability long-term. Maintenance and improvements of A0REF will be an ongoing requirement for using it in absolute positioning validation in the future.

The experimental platform can be iterated and improved upon for increased usefulness. Methods need to be developed for repeating the heading approach and the on-board baseline as a reference approach. This includes calibrated baselines, measurement uncertainty analysis as well as offset correction from any system to be compared.

Lastly a rigid measurement uncertainty analysis needs to be performed for a laser tracker to be used properly in kinematic positioning validation. To be able to validate moving target this measurement uncertainty analysis needs to consider both 3D positioning and timing.

6.7 Delivery to FFI-goals

The FFI goals for the Electronics, Software and Electronics (EMK) program are subdivided in six areas:

1. Electrical Architecture – inside the vehicle
2. Architectures outside the vehicle – the connected system
3. Cybersecurity
4. Man-Machine Interaction
5. Verification and Validation
6. Technology for Green, Safe, Automated and Connected Functions

The NPAD project concerns mainly area 6 - Technology for Green, Safe, Automated and Connected Functions. Below the relevant goals of the subareas is compared with what has been achieved in NPAD.

FFI-Goal: To develop necessary base technologies on component level in order to realize functions. For "safety functions" and "automated functions" it is primarily control functions including sensor technologies.

NPAD delivery: GNSS based positioning is a base technology for creating safe automated functions. Large volumes of automated vehicles and other applications using GNSS N-RTK positioning with cm-level accuracy will require an efficient distribution of N-RTK correction data that scales with large number of users. NPAD has implemented and tested the 3GPP standard providing an efficient transmission from the correction data service provider (e.g. SWEPOS) to the client GNSS receiver which is a necessity considering the large volume of future users.

6.8 Deliverables and Reports

Several reports and deliverables have been produced within the project. All deliverables, except for deliverable D1.3 Final Report, are project internal and not public.

List of deliverables:

D1.3 Final Report (public)

D2.1 Positioning requirements for Automated Driving applications

D3a.1 VRS grid data handling protocol

D3a.2 System Design Document - GNSS RTK components

D3a.3 System Design Document - Client device end

D3a.4 Scalable NRTK correction data provisioning system

D3a.5 Test Procedure Document

D3a.6 Report on system Design Specification

D3b.1 System Design Document – Einride

D3b.2 System Design Document - Test Platform

D3b.3 Integrated Navigation Solution in Einride Platform

D3b.4 Test platform

D4.1 Test Procedure Document

D4.2 Complete end to end integrated system for Einride

D4.3 Complete end to end integrated system for Test platform

D4.4 Positioning reference system for validation and calibration of positioning systems

D5.1 Accuracy evaluation method for GNSS-positioned vehicles

D5.2 Results from accuracy evaluation

D5.3 Demonstrators

7 Dissemination and publications

7.1 Dissemination

The project and the results have been presented both at internal meetings within each partner's organization and at the following external forums and conferences:

- 2018-02-05 at the Swedish Radio Navigation Board seminar in Stockholm
- 2018-03-20 at Kartdagarna in Linköping
- 2018-05-16 at ENC2018 conference in Gothenburg
- 2018-05-18 at Mätkart conference in Borås
- 2018-11-15 at EUPOS conference in Tallin
- 2018-11-29 at the Swedish Radio Navigation Board seminar in Stockholm
- 2019-03-20 at the Position2030 conference in Kista, Stockholm
- 2019-03-21 at the Swedish Radio Navigation Board seminar in Stockholm
- 2019-04-15 poster at EFTF conference in the USA.
- Article about NPAD in Fordonskomponenten issue no 2 2019
- 2019-10-16 at the Vinnova FFI conference in Gothenburg
- 2019-10-23 at the GNSS seminar arranged by Lantmäteriet in Gävle.
- 2020-02-04 at the Swedish Radio Navigation Board seminar in Stockholm
- 2020-11-26 at the NPAD final event seminar (online event)

At the end of the project, an NPAD Final Seminar was held as an online event on November 26th with around 50 participants.

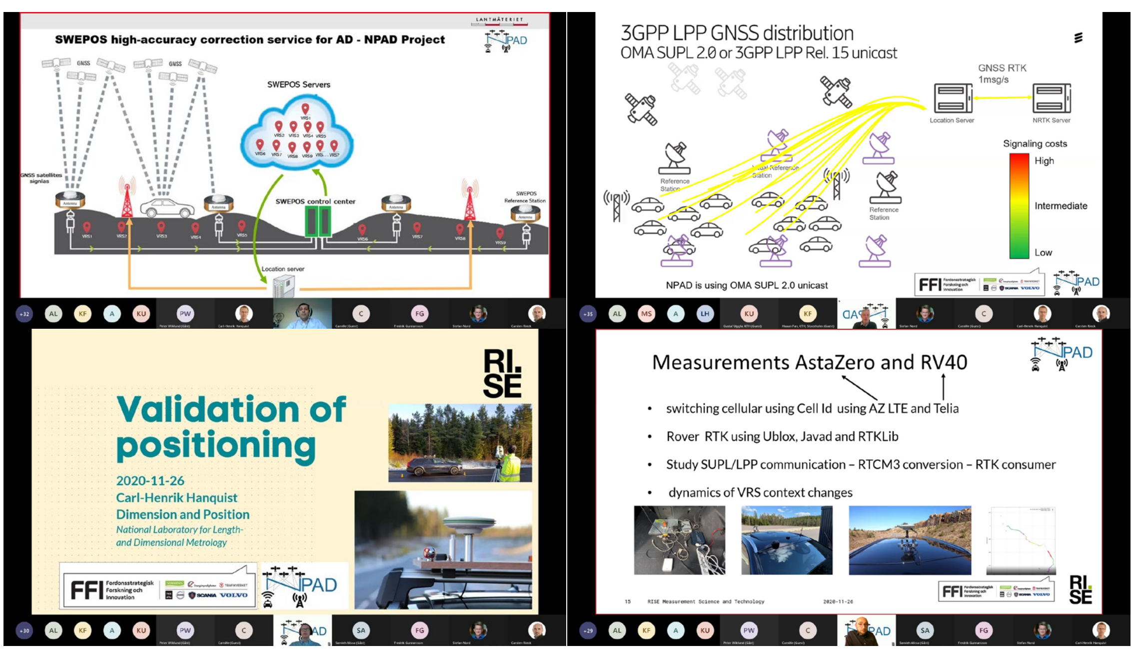


Figure 86 Screenshots from the NPAD Final Seminar Online event on Nov 26th 2020.

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	
Be passed on to other advanced technological development projects	X	Passed on to H2020 project "PREPaRE Ships", the "P N K UTM for UAV" project sponsored by Trafikverket and the Vinnova FFI project "VAMLAV".
Be passed on to product development projects	X	Part of product development at Ericsson, Lantmäteriet, Einride and Waysure
Introduced on the market		
Used in investigations / regulatory / licensing / political decisions		

NPAD has as mentioned above been linked with other external projects that will accelerate and give a greater impact of the results from NPAD:

- H2020 project PREPaRE Ships will use parts of the VRS grid provisioning system developed by Lantmäteriet [9].
- Another domain that will use the NPAD results: UAV:s.
  A project sponsored by the Swedish Road Authority named "Positioning, Navigation and Communication UTM for UAV's", will use the results from NPAD for UAV's [10].
- Vinnova FFI project VAMLAV benefits from the work relating to positioning validation and A0REF [34].

7.2 Publications

A publication for ION GNSS+ was planned for 2020 but was delayed due to Covid19. It is planned to submit an abstract for ION GNSS+ 2021 regarding a concept on how to handle ambiguity harmonization when the GNSS-receiver switches from one VRS to another. Besides that and presentation material provided at the different events according to the list in section 7.1 above, the only publication has been an article in Fordonskomponenten issue no 2 2019.

8 Conclusions and future research

8.1 Conclusions

NPAD has implemented and tested the Network-RTK correction data distribution system according to the 3GPP Rel 15 standard, and also implemented the needed software at the GNSS client side in order to test the distribution mechanism and how this is handled by a Network-RTK enabled GNSS receiver. Three different GNSS platforms has been developed for testing the NPAD concept:

1. The GOOFY platform developed by Waysure for integration and test in the Einride vehicle.
2. The Ericsson platform based on a RTKLib implementation on a Raspberry Pi with u-blox GNSS receiver.
3. The RISE test platform based on the GNSS Client software developed by Waysure integrated on a Raspberry Pi platform together with a 4G modem. This platform provided an RTCM correction data stream that was used with different GNSS receivers e.g. Javad, Trimble and u-blox.

The main conclusion of the results show clearly that the Network-RTK distribution system works and allows a large number of GNSS clients. The handling of changing from one VRS to another still needs to be handled at the GNSS client and this can be done with several different methods in combination with sensor fusion with other sensors like e.g. IMU:s and vehicle onboard sensors.

The project has also made a survey on different methods on how to validate the dynamic accuracy of an onboard positioning system as well as performed some initial tests with e.g. laser trackers and the “LEAF platform” built and used for this purpose. The results show that this is a quite complex task to solve and more work will be needed to have a robust method in order to validate the dynamic positioning accuracy.

The A0REF reference system created within the scope of the project is a good start in order to provide so called “anchor points” with high accuracy that could be used as references for other measurements and equipment.

8.2 Future Work

The purpose of this section is to provide a list of topics that can serve as input for decisions for future research and development activities. It can e.g. be work that was identified during the project as extensions but had to be put aside for budget and/or resource reasons. It can also be topics that did not fall within the project scope but that still is of importance and interests of the partners and that need further research and development to develop measurement technologies and methods.

- As the project did not involve any telecom operators it was not possible to implement and test broadcast of N-RTK correction data via the cellular network. We could to some extent emulate this by switching VRS based on what associated Cell Id a 4G modem was connected to, but in the future, a telecom operator should be involved to be able to test broadcast in full extent. The telecom operator also must be involved when setting up the business model for this kind of service in cooperation vid Lantmäteriet.

- NPAD only handled correction data for Network-RTK which is an Observation Space Representation (OSR), but the 3GPP standard also supports State Space Representation (SSR). In future project SSR should also be implemented and tested.
- The 3GPP standard also deals with integrity, and this is something that a future project should spend more work on. For critical applications like automated driving, the integrity of the GNSS receiver system is of great importance and all functionality that could support the integrity should be investigated and evaluated. Standardized integrity metrics should be used.
- The VRS grid setup was limited to the test areas and more work on different methods on how design and distribute the VRS grid will also need more future work. Also, the business model of Lantmäteriet compared with the one used today will need further investigations
- As mentioned in section 6.5.2.5, future work related to NPAD also includes the concept of a combined middleware allowing to harmonize VRS carrier phase ambiguities, formation of VVRS entities and the introduction of UTC(SP) traceable timing in the (V)VRS observations
- As mentioned in section 6.6.3.4, maintenance and improvements of A0REF will be needed for using it in absolute positioning validation in the future. Additionally, the experimental platform will need to be iterated and improved to match future requirements. This includes calibrated baselines, measurement uncertainty analysis as well as offset correction from any system to be compared.
- As mentioned in section 6.5.3.6, AstaZero have a specific interest of exploring a reduced version of the developed software for their 4G modems.

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